



Design & Manufacture of Gas Turbines for Aircraft

by

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<http://www.sussex.ac.uk/profiles/9815>

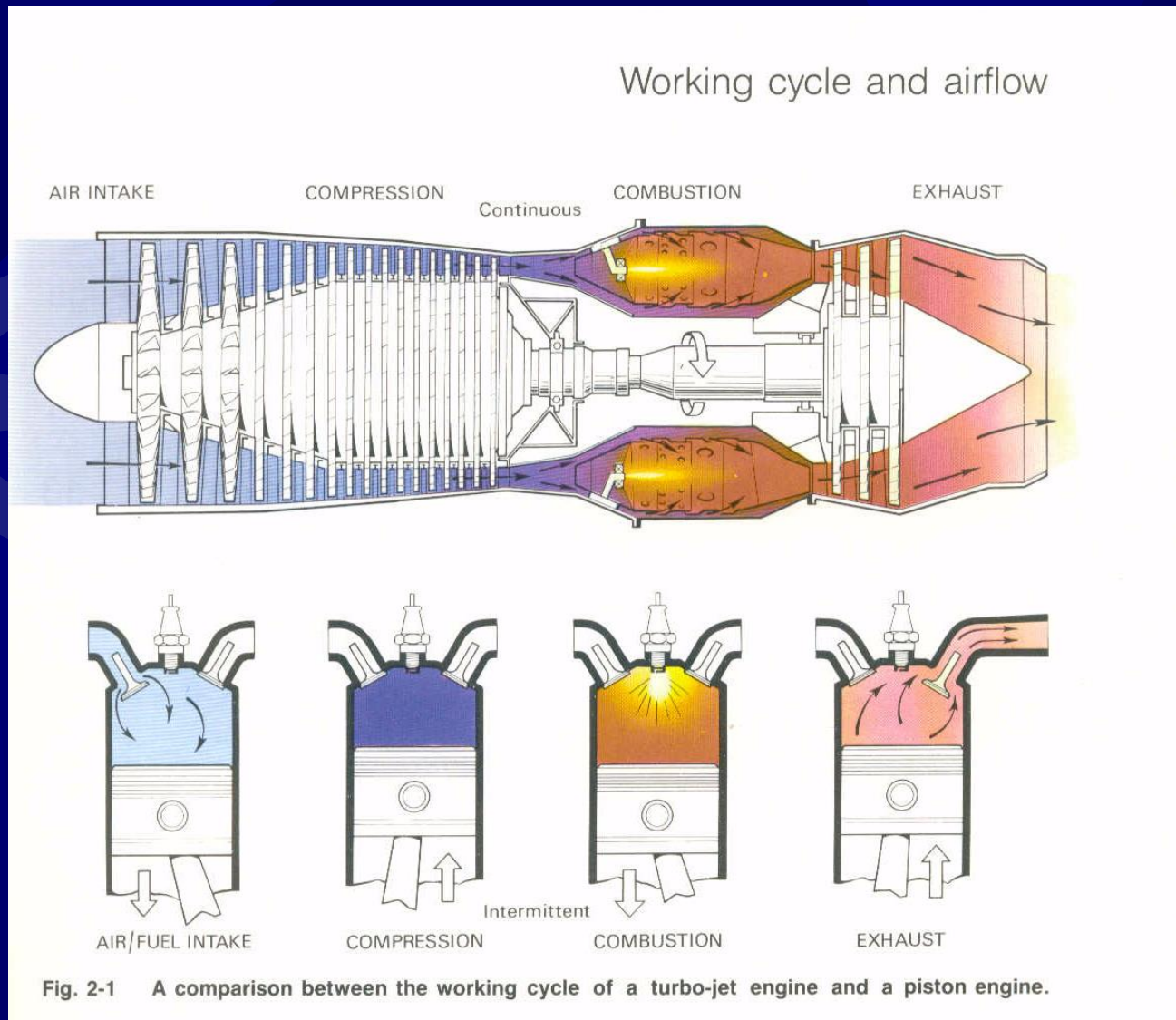
Systems

- ✱ Compressor
- ✱ Combustion chambers
- ✱ Turbines
- ✱ Exhaust system
- ✱ Accessory drives
- ✱ Lubrication
- ✱ Internal air system

Systems not covered

- ✱ Fuel system
- ✱ Starting and Ignition
- ✱ Controls and instrumentation
- ✱ Ice protection
- ✱ Fire protection
- ✱ Thrust reversal
- ✱ Afterburning

Working Cycle



Compressor

- ✱ From the front to the rear there is a gradual reduction in annulus area between the rotor shaft and the stator casing
- ✱ This maintains a near constant air axial velocity as the density increases through the length of the compressor
- ✱ The convergence of the air annulus is achieved by the tapering of the casing or rotor

Compressor

- ★ A single spool device consists of one rotor assembly and stators with as many stages as is necessary to achieve the desired pressure ratio. All the intake passes through the compressor.
- ★ The multi-spool compressor consists of two or more rotor assemblies, each driven by their own turbine at an optimum speed to achieve higher pressure ratios and to give greater operating flexibility.
- ★ Multi-spool is most suitable for by-pass engines which give higher efficiency

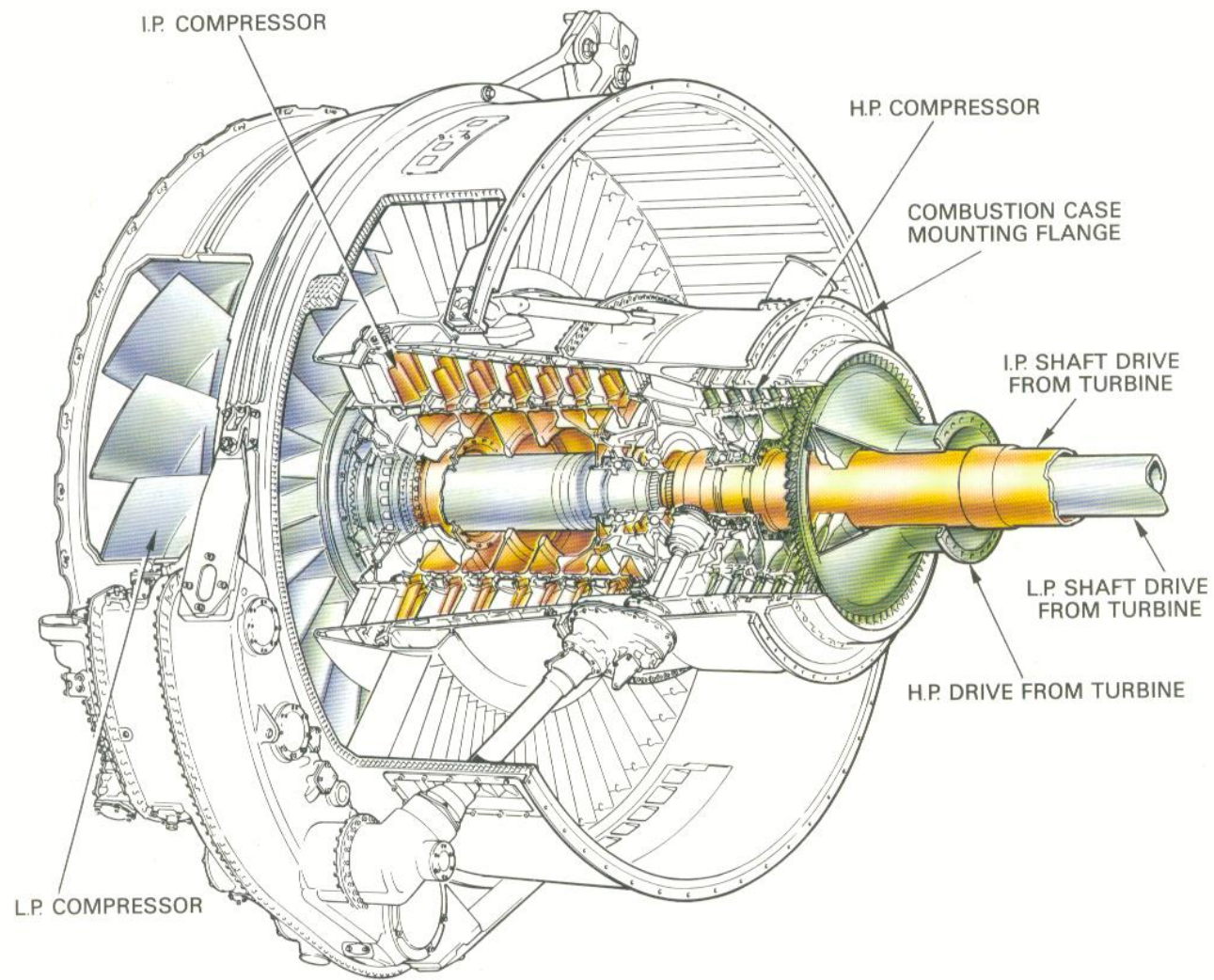
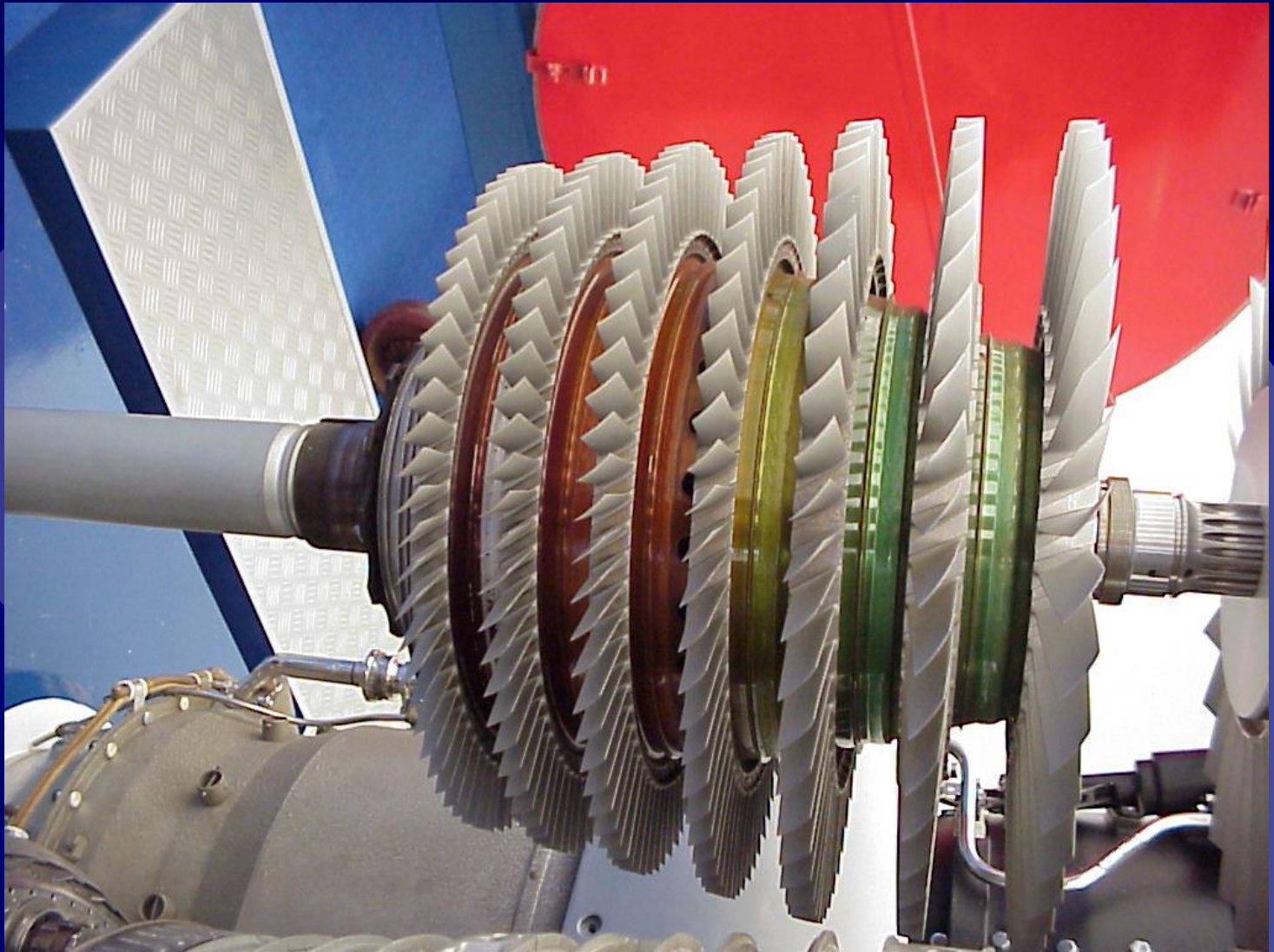


Fig. 3-8 Typical triple spool compressor.

Construction

- ✱ The construction of the compressor centres around the rotor assembly and casings
- ✱ The rotor shaft is supported in ball and roller bearings and coupled to the turbine shaft in a manner that allows for any slight variation of alignment.
- ✱ The cylindrical casing assembly may consist of a number of cylindrical casings with a bolted axial joint between each stage; or the casing may be in two halves with a bolted centre line joint.
- ✱ One or other of these construction methods is required in order that the casing can be assembled around the rotor.



Rotors

- ✱ The disc is required to support the centrifugal blade load.
- ✱ Where a number of discs are fitted onto one shaft they may be coupled and secured together by a mechanical fixing but generally the discs are assembled and welded together at the periphery, thus forming an integral drum.
- ✱ Figure 3-11 illustrates blade fixing. Fixing may be circumferential or axial to suit the special requirements of the stage.
- ✱ For small machines the blades may be produced integral with the disc, a blisk

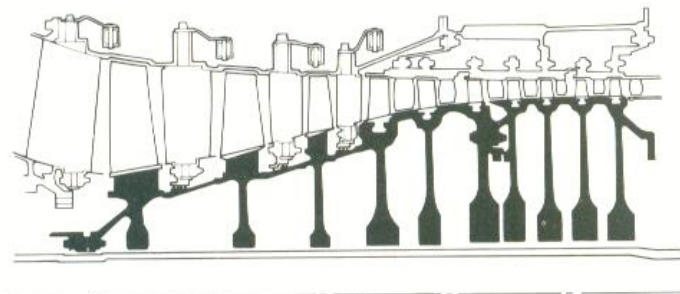
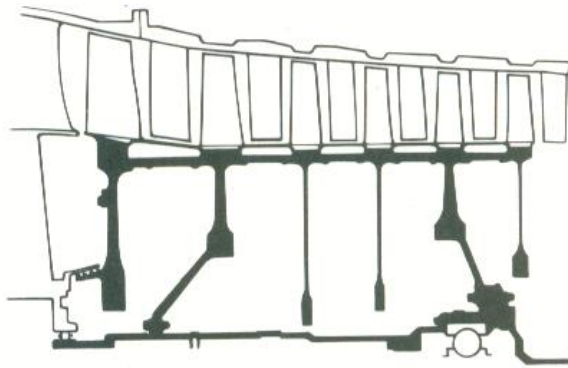
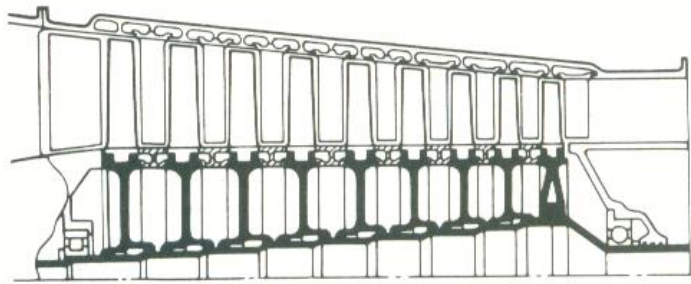


Fig. 3-10 Rotors of drum and disc construction.

Tapered flow annulus gives constant axial velocity with increasing density

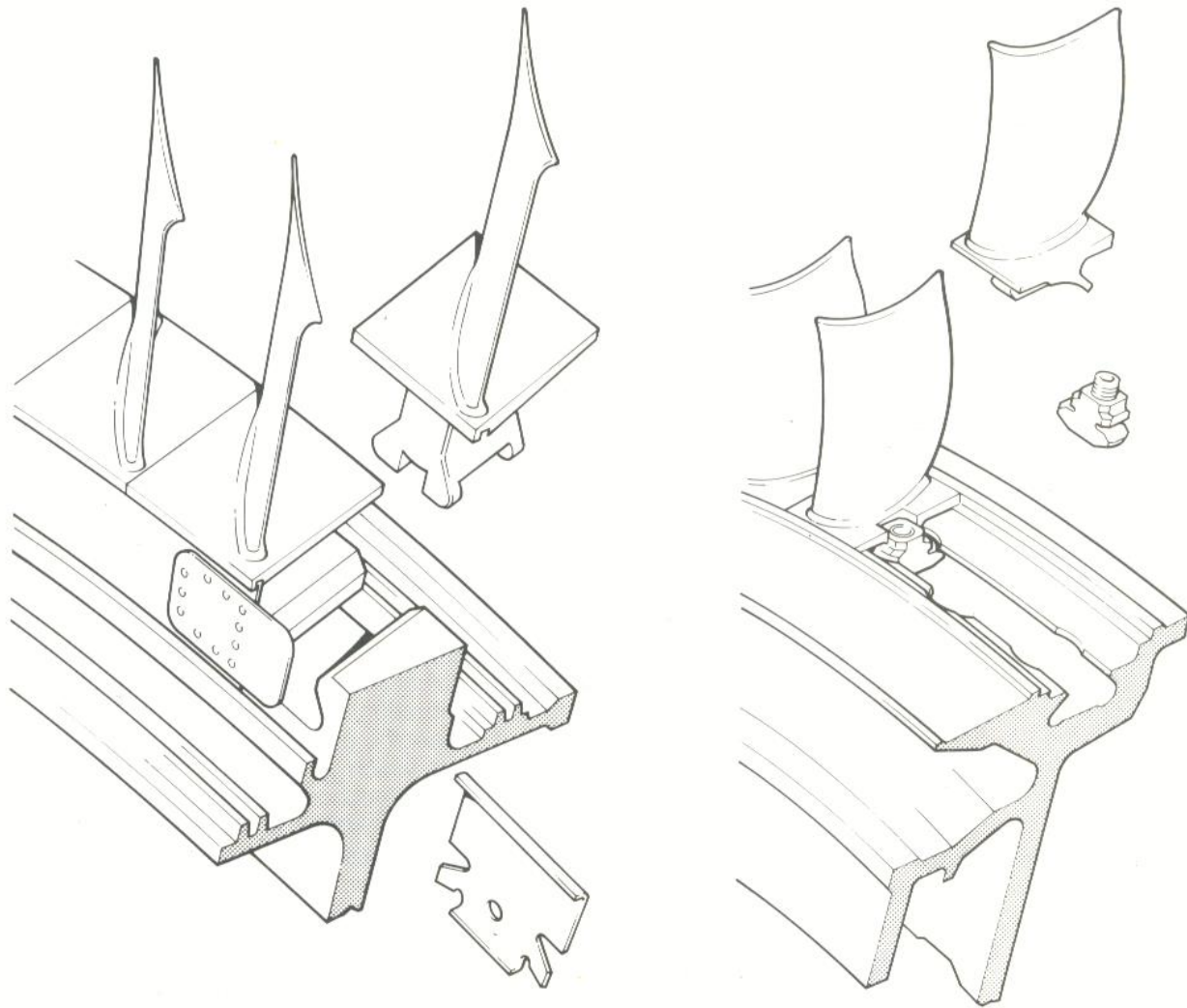


Fig. 3-11 Methods of securing blades to disc.

Stator vanes

- ✱ Stator vanes are secured into the compressor casing or into stator vane retaining rings, which are themselves secured to the casing.
- ✱ The vanes are often assembled in segments in the front stages.
- ✱ It is also necessary to lock the stator vanes in such a manner that they will not rotate around the casing.

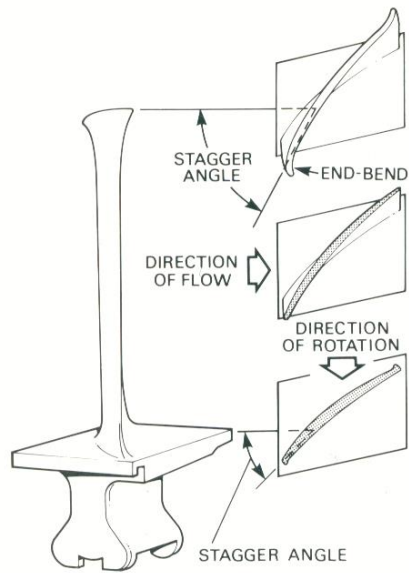


Fig. 3-12 A typical rotor blade showing twisted contour.

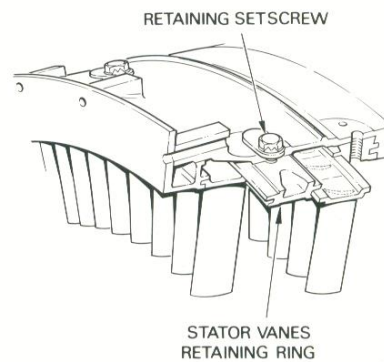
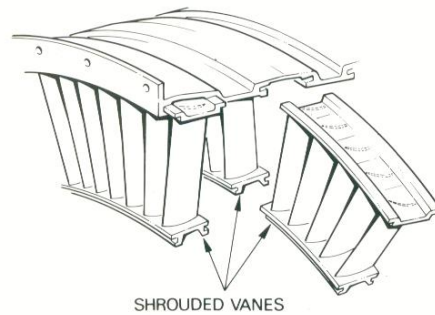
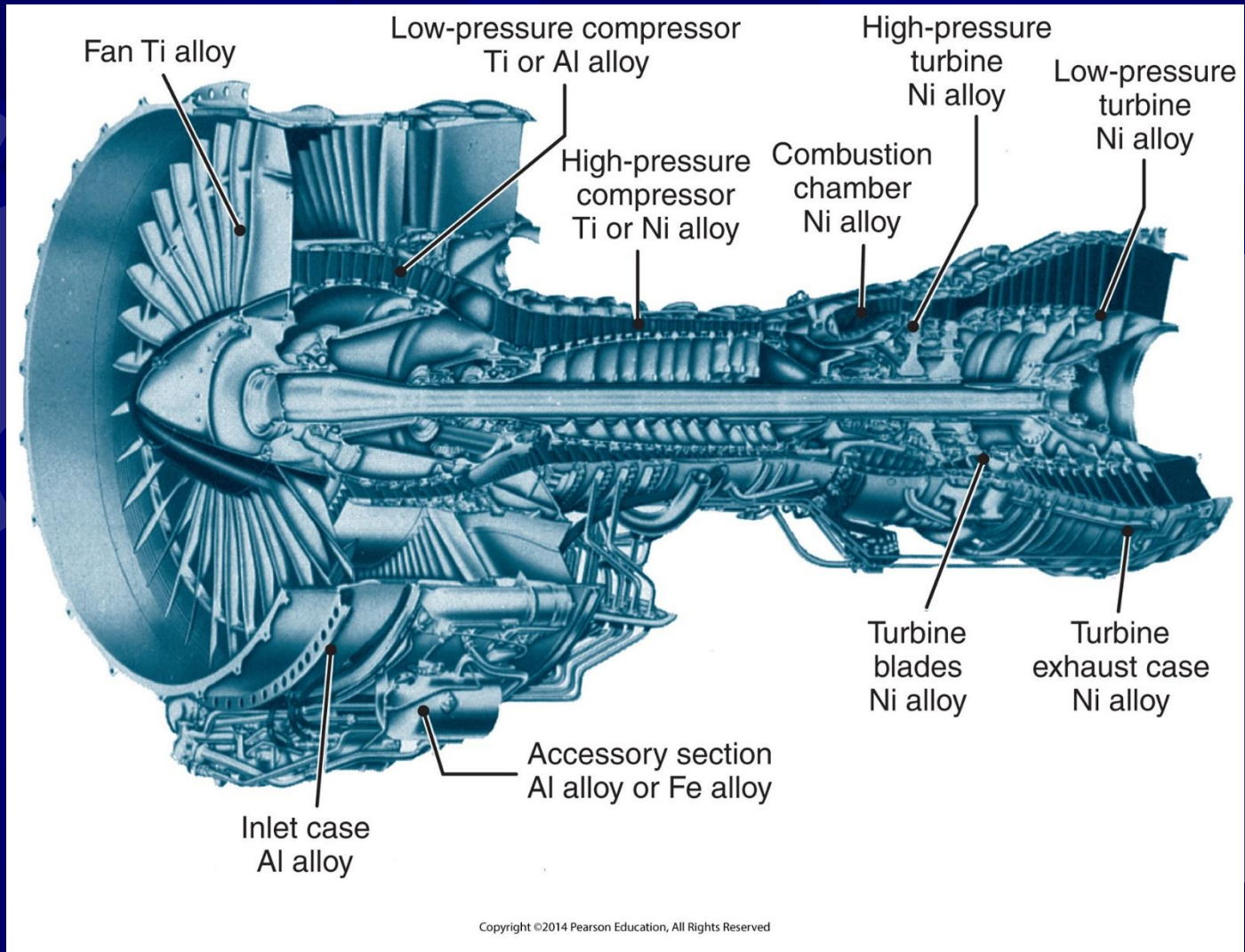


Fig. 3-13 Methods of securing vanes to compressor casing.

Cross-section of a jet engine (PW2037), showing various components and the alloys used in manufacturing them. *Source:* Courtesy of United Aircraft Pratt & Whitney.



Materials

- ✱ The lightest most cost effective design that technology allows for the given loads and temperatures prevailing.
- ✱ Aluminium at the front of the compression system followed by alloy steel as the compression temperature increases.
- ✱ At the final stages where temperature exceeds the capability of the best steel, nickel alloys may be required.
- ✱ The use of titanium in preference to aluminium and steel is now more common, especially in military engines

Materials – stator vanes

- ✱ Stator vanes are normally produced from steel or nickel based alloys.
- ✱ Titanium may be used in the low pressure area but is unsuitable for smaller vanes in the the high pressure high temperature region rearward.
- ✱ Any excessive rub between rotating and static components can generate sufficient heat to ignite the titanium

Materials – discs, drums and blades

- ☀ Centrifugal forces dominate, thus we require metals with highest ratio of strength to density.

<http://www.youtube.com/watch?v=j973645y5AA> engine test

- ☀ Titanium is the preferred material and has replaced steel alloys.
- ☀ As higher temperature titanium alloys are developed, they are progressively displacing nickel alloys for the disc and blades at the rear of the compressor.

High by-pass ratio blade

- ✱ Must be very light for the engine to withstand the large out of balance forces that would result from a blade failure
- ✱ Conventional designs are machined from solid titanium forgings, lossey snubbers are required for this type of blade
- ✱ Wide chord fan blades do not require snubbers
- ✱ The weight is maintained at a low level by fabricating the blades from skins of titanium incorporating a titanium honeycomb core also carbon fibre composites are used



Fig. 3-19 Typical types of fan blades.

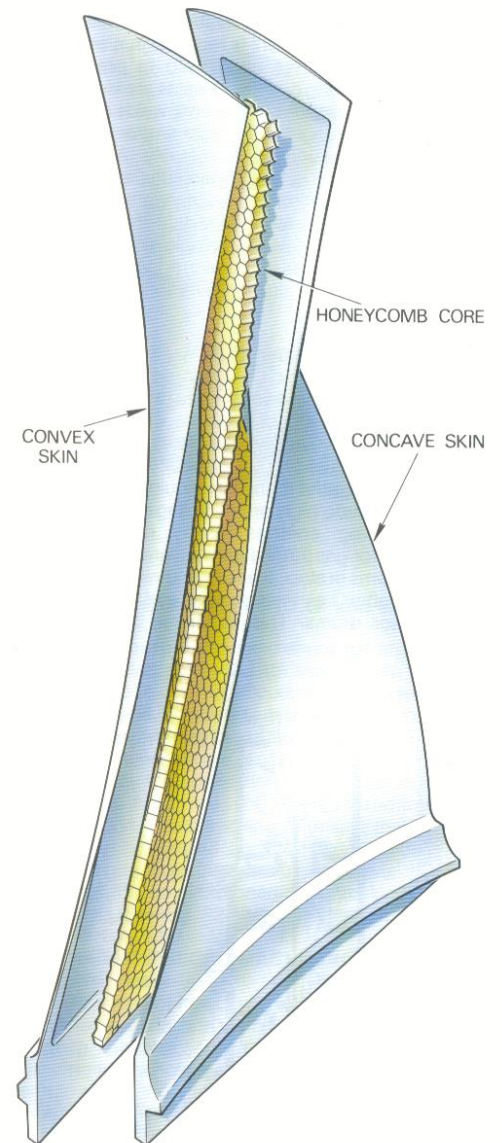


Fig. 22-6 Wide chord fan blade construction.

Trent XWB Engine for the A380 Airbus





GE90 fan, 100% defect-free, carbon-reinforced epoxy blade - which means no wrinkles or voids in the fibers. To do that required modeling of the composite process, advanced sensor and data acquisition systems, data-to-information conversion technologies, compression molding presses, autoclaves and small-scale molds to simulate processes

GE90



<https://www.youtube.com/watch?v=-XJYG8fxWhA> technology development

<https://www.youtube.com/watch?v=eoNySabChvA> manufacture of blade

Ceramic Matrix Composites

- ★ https://www.youtube.com/watch?v=is1B_BilkyUM
- ★ GE mass-produce silicon carbide (SiC) materials used to manufacture ceramic matrix composite components (CMCs) for jet engines and land-based gas turbines.

Trent XWB Rolls Royce Engine

- Three-shaft high bypass ratio: 9.3
- Take-off thrust: 75,000–97,000 lbf (330–430 kN) (flat-rated to ISA+15C)
- Fan diameter: 3.0 m (118 in)
- Fan: single stage, swept, low hub:tip ratio
- Airflow: approx. 1,440 kg (3,170 lb) per second
- Overall pressure ratio $\geq 52:1$ (Top-of-Climb)
- IP compressor: 8 stage axial
- HP compressor: 6 stage axial
- Combustor:
 - HP turbine: single-stage, aircooled
 - IP turbine: two-stage, aircooled (extra stage relative to previous marks of Trent)
 - LP turbine: 6-stage, uncooled

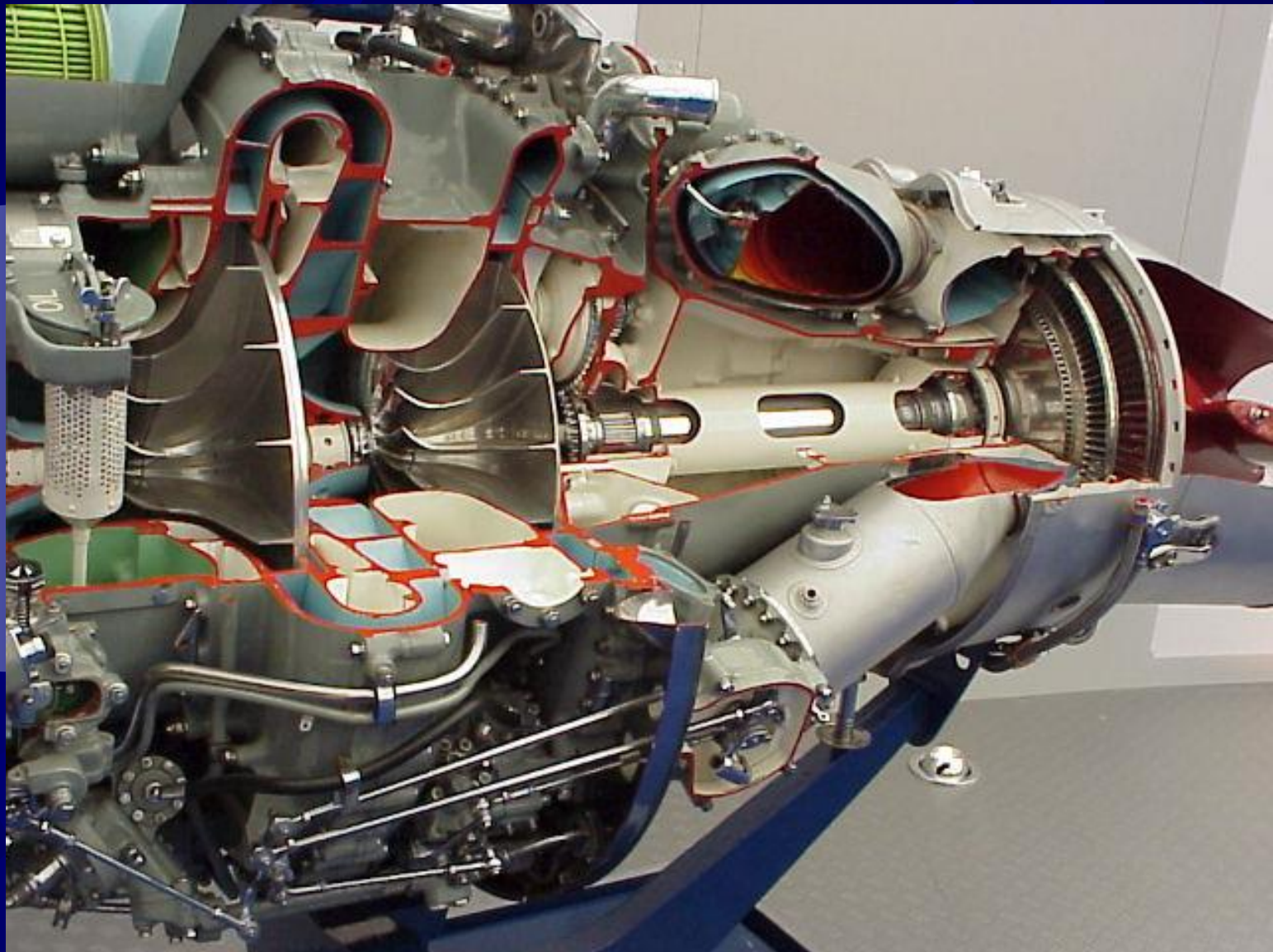
1.1 Turbine Gas Temperature (°C):

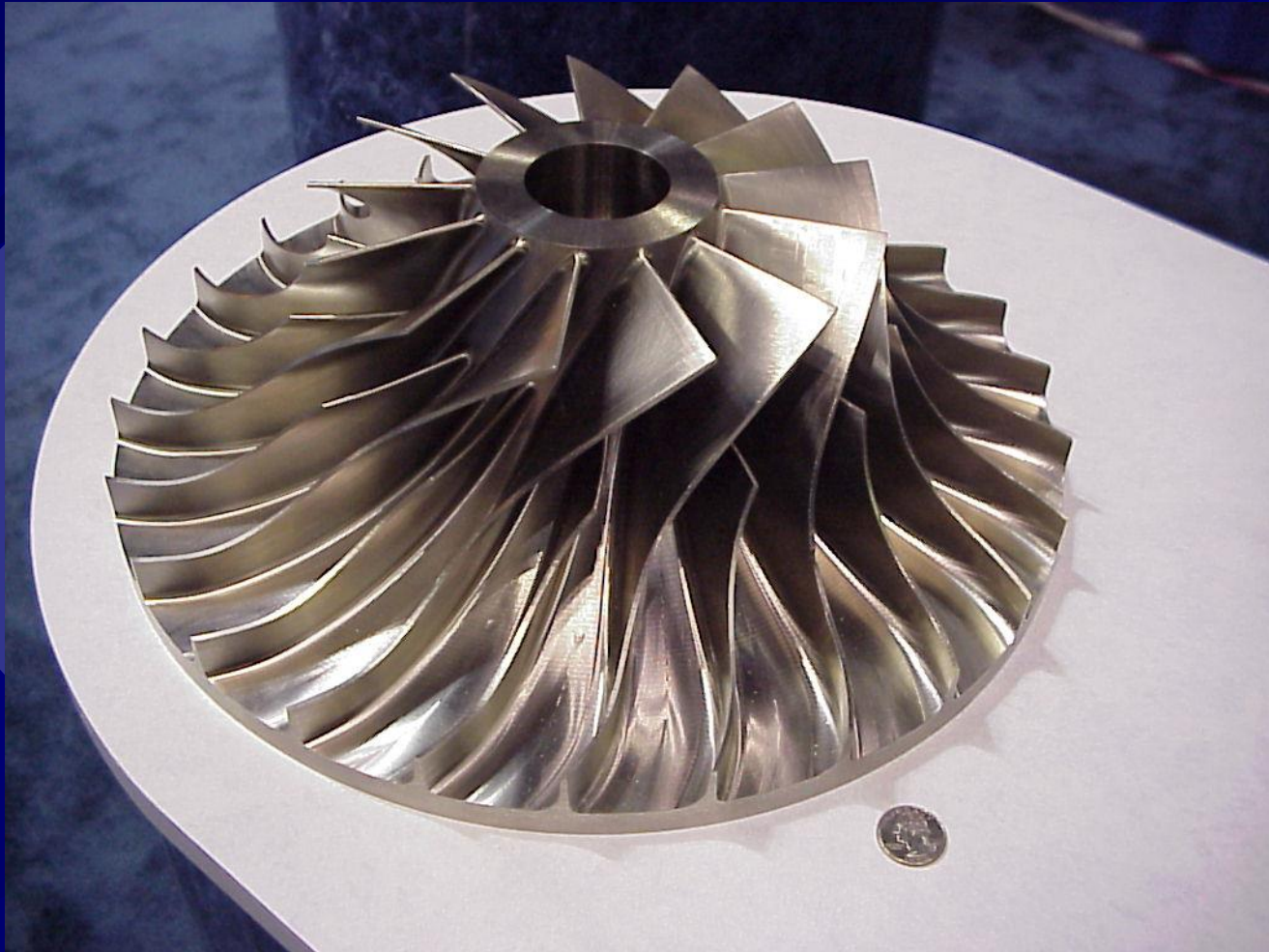
Turbine Gas Temperature (TGT) is measured by thermocouples positioned at the stage Vane of the LP Turbine.

	Maximum TGT Trimmed (Displayed) (°C)
Take-Off (5 minutes)	900
Maximum Continuous	850
Ground start and shutdown	700
In-flight relight	900
Maximum exhaust gas over temperature (*)	920

Materials – centrifugal compressor

- ✱ Titanium is normally specified though aluminium may still be used on the largest low pressure ratio designs where robust sections give adequate ingestion and temperatures are acceptably low.





Combustion Chamber

- ✱ The containing walls and internal parts must be capable of resisting the very high gas temperature in the primary zone
- ✱ This is achieved by using the best heat resisting materials available, the use of high heat resistant coatings and by cooling the inner wall of the flame tube as an insulation from the flame.
- ✱ The combustion chamber must also withstand corrosion due to the products of combustion, creep failure due to temperature gradients and fatigue due to vibrational stresses.

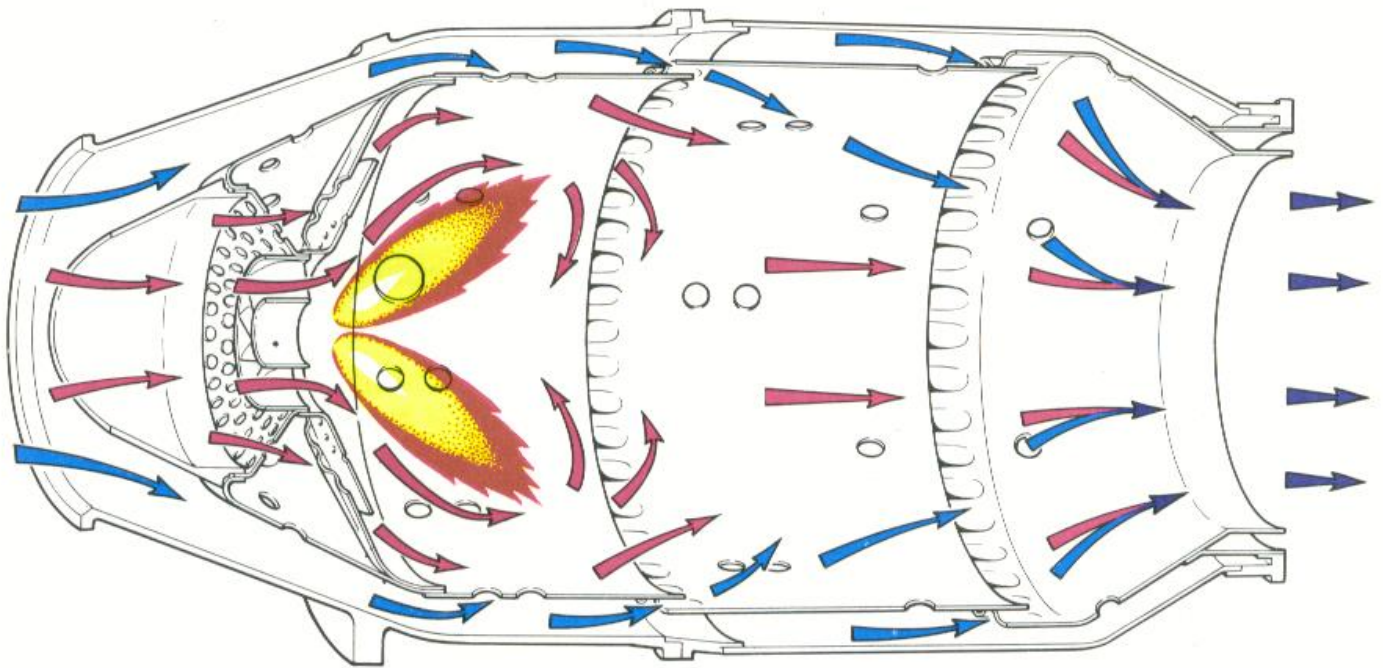


Fig. 4-3 Flame stabilizing and general airflow pattern.

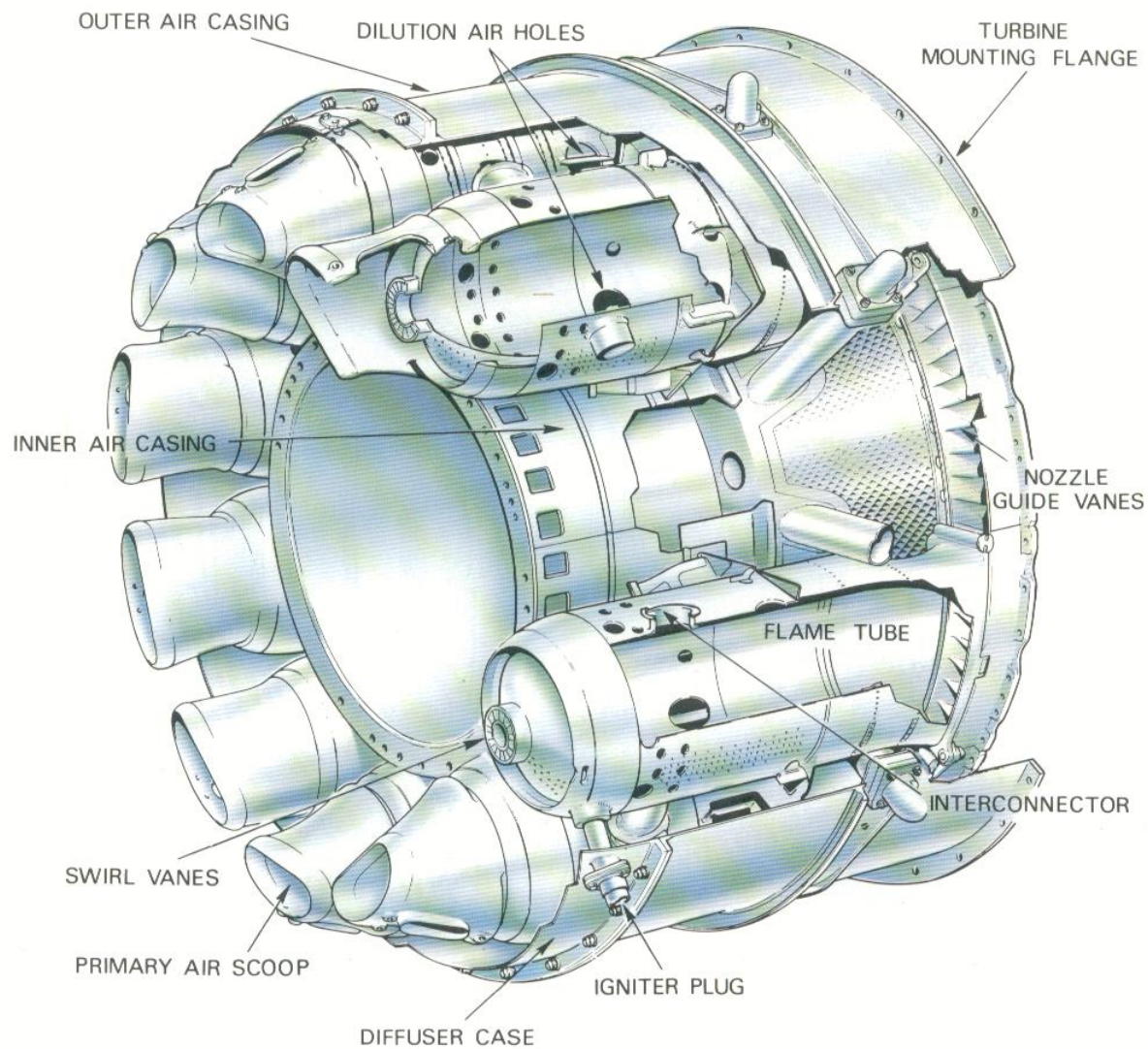
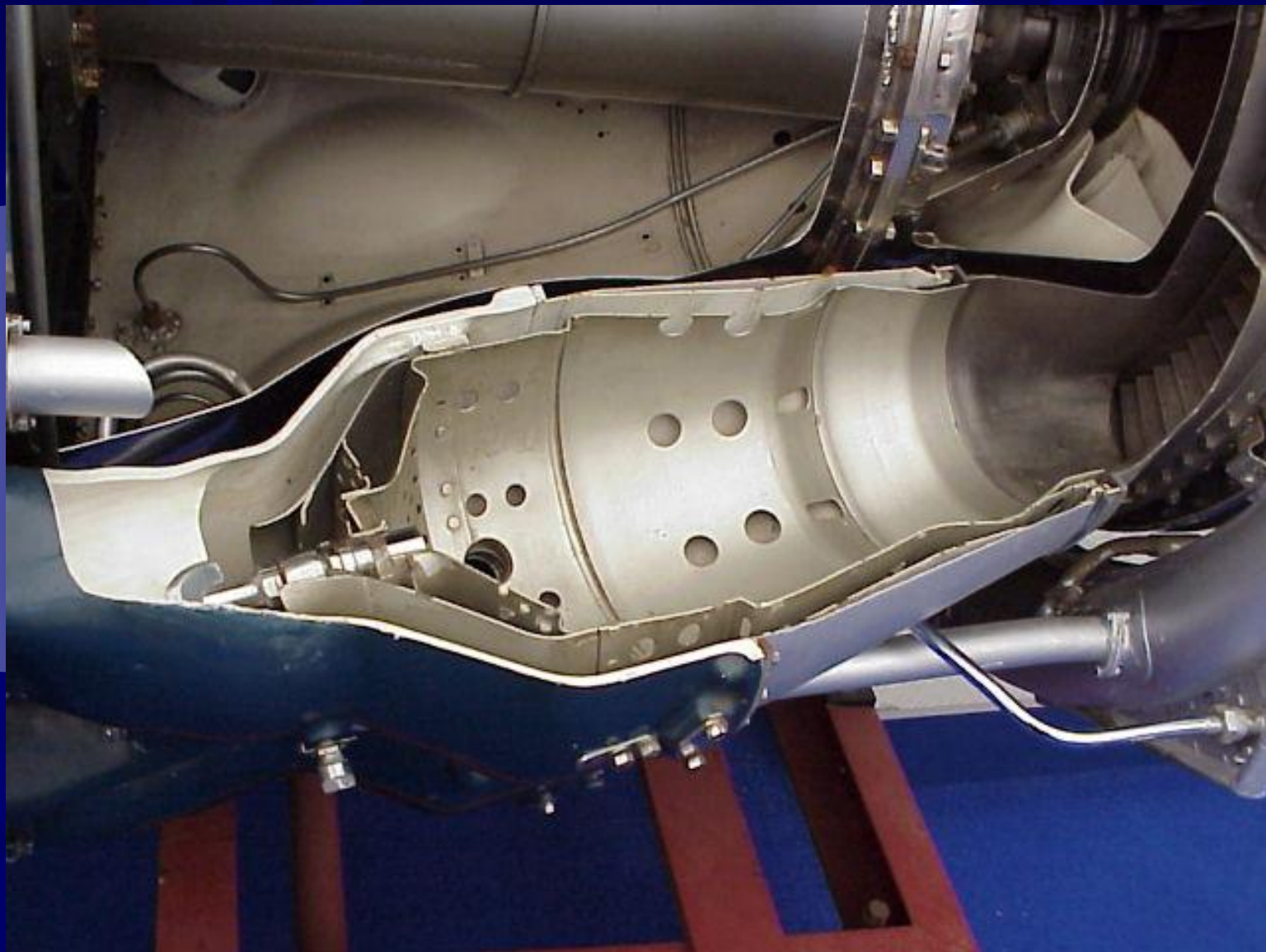


Fig. 4-8 Turbo-annular combustion chamber.



Turbine Construction

- ★ The basic components are:
 - ★ Combustion discharge nozzles
 - ★ Nozzle guide vanes
 - ★ Turbine discs
 - ★ Turbine blades
- ★ The rotating assembly is carried on bearings mounted in the turbine casing
- ★ The turbine shaft may be common to the compressor shaft or connected to it by a self aligning coupling

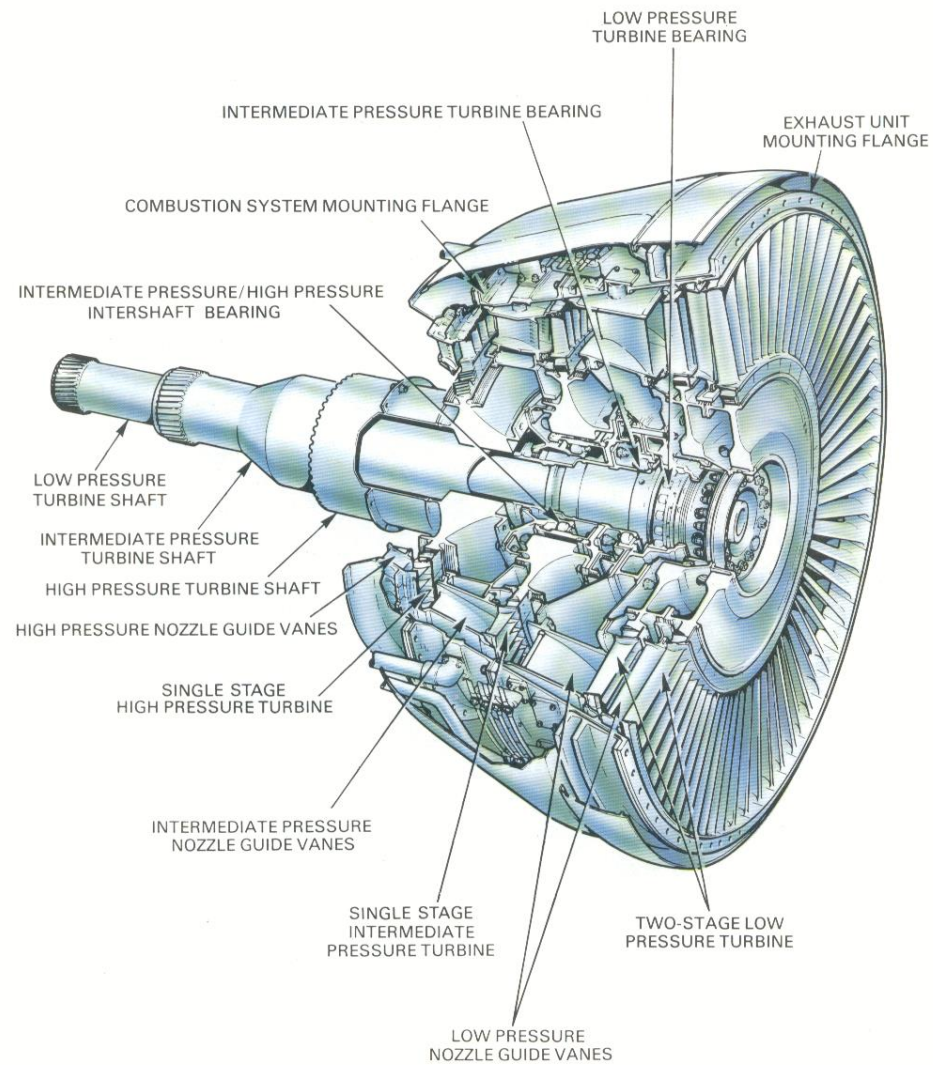


Fig. 5-3 A triple turbine and shaft arrangement.

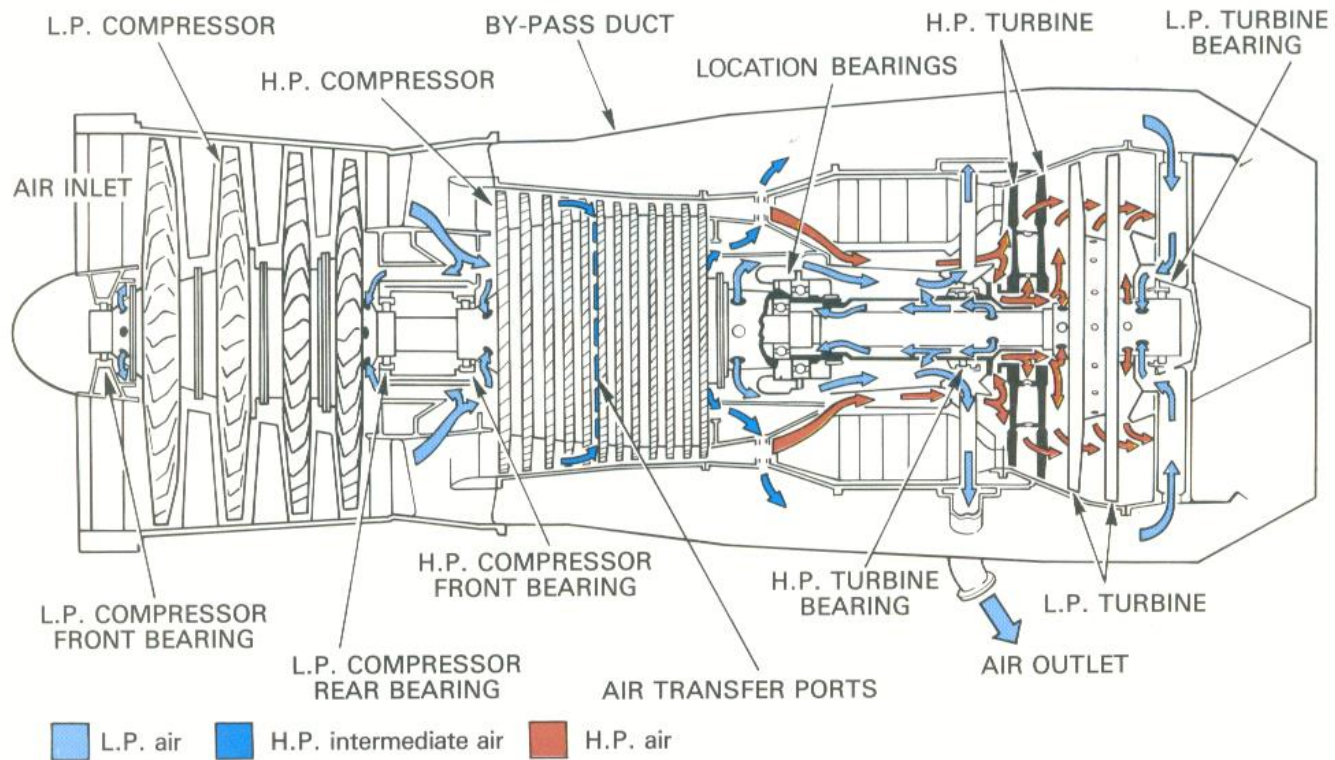


Fig. 9-1 General internal airflow pattern.

Nozzle guide vanes

- ★ The convergent nozzle guide vanes are located in the turbine casing in a manner that allows for expansion
- ★ Usually hollow so that they can be cooled by passing compressor delivery air through them

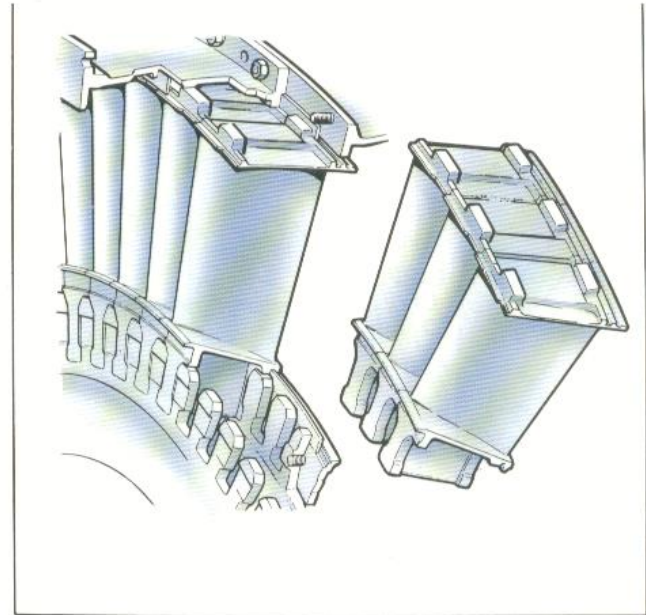
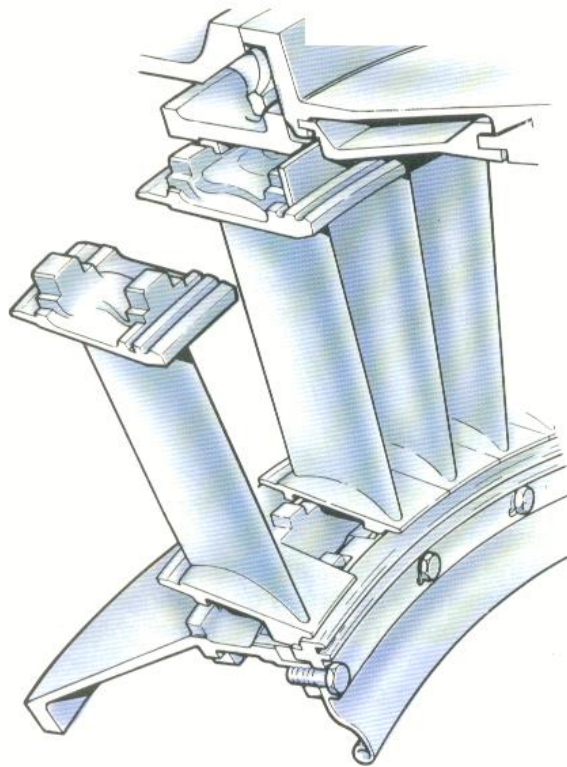
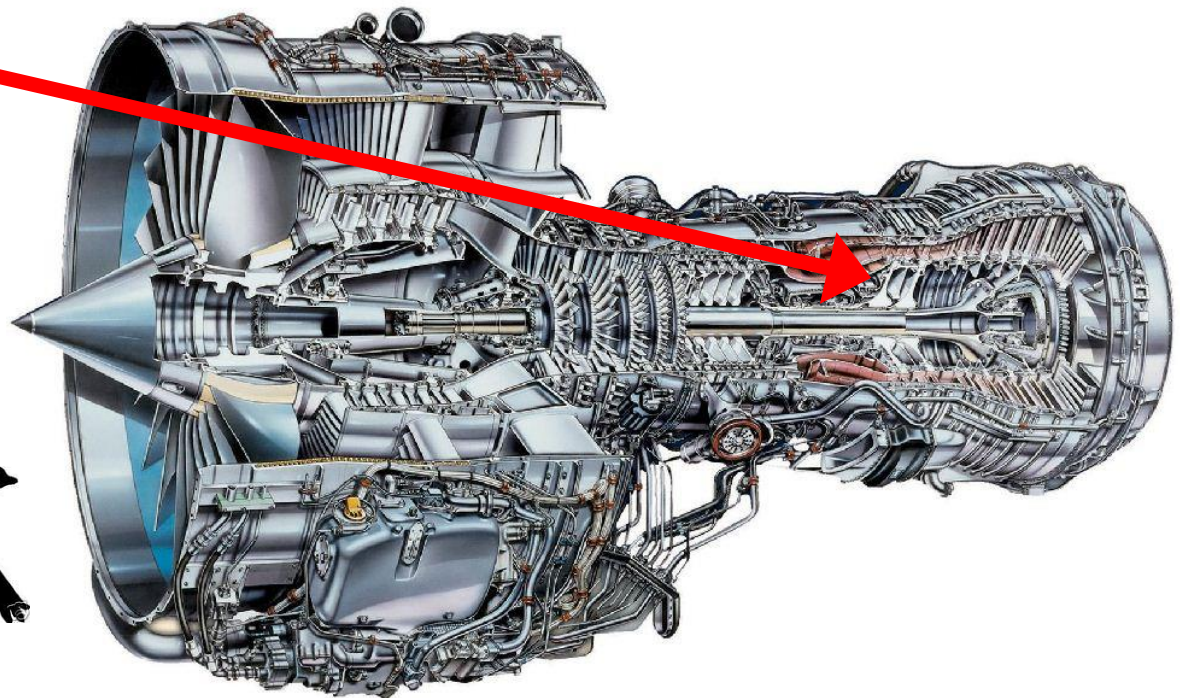
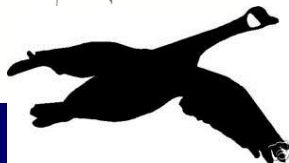
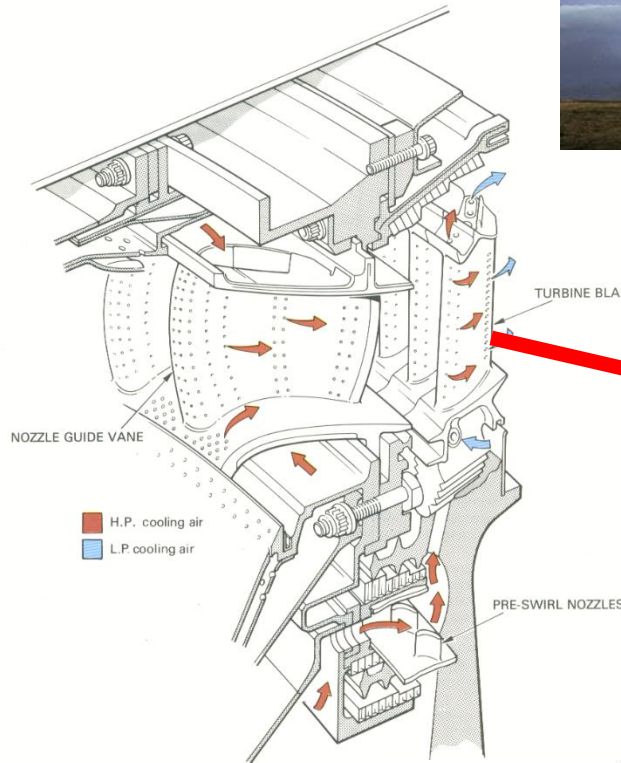


Fig. 5-8 Typical nozzle guide vanes showing their shape and location.

Trent XWB Engine for the A380 Airbus





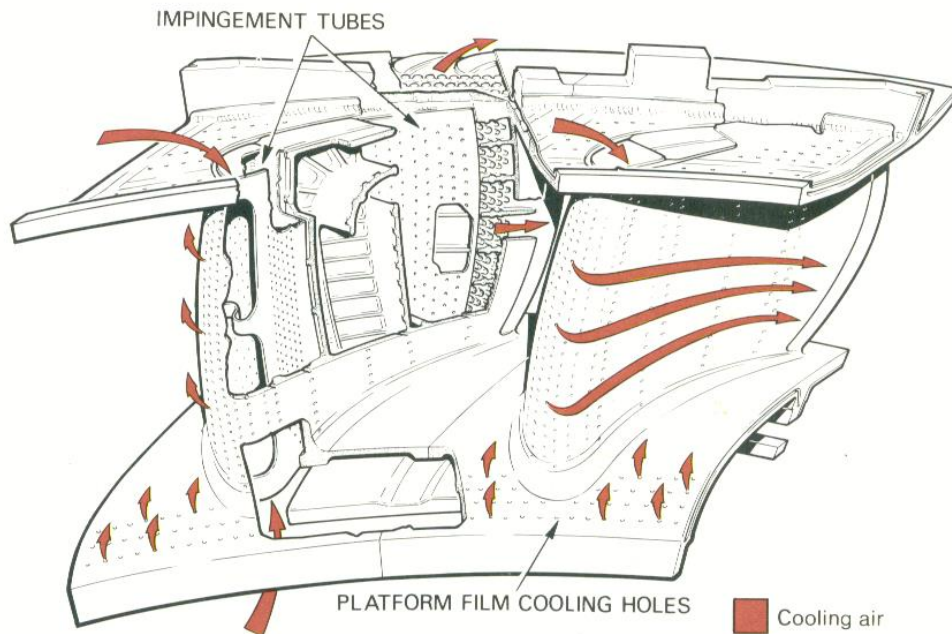
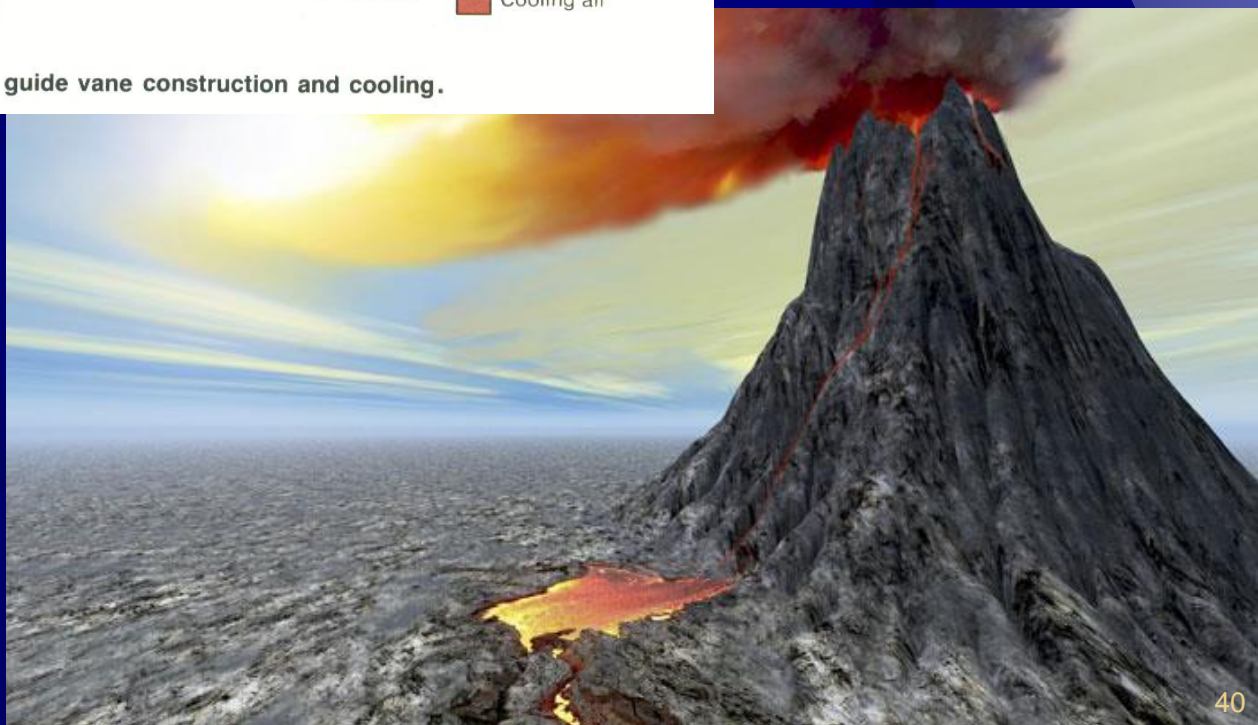


Fig. 9-4 High pressure nozzle guide vane construction and cooling.



High Pressure Single Crystal Turbine Blade & Disc Manufactured from Nickel Super Alloys



Turbine discs

- ★ Discs are usually manufactured from a machined forging with an integral shaft or with a flange onto which the shaft may be bolted.
- ★ The disc also has, around its perimeter, provision for the attachment of the turbine blades.
- ★ The discs are cooled on both sides to limit conduction from the blades
- ★ The method of attaching the blades to the disc is very important, since the stress in the disc around the fixing or in the blade root limits the rim speed.

Engineering Failure Analysis 13 (2006) 9–17 – Elsevier Witek

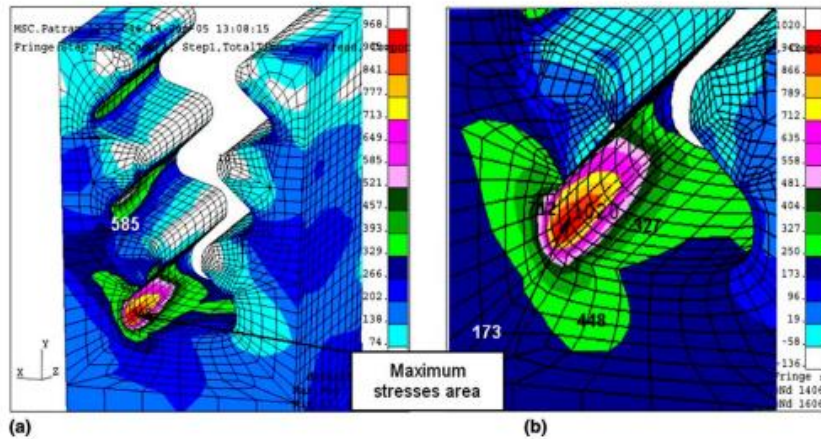


Fig. 7. Von Mises (a) and maximum principal (b) stress distribution in the vicinity of the serration area of disc for speed of 13,500 rpm.

☀ Operational speed 12,500 rpm

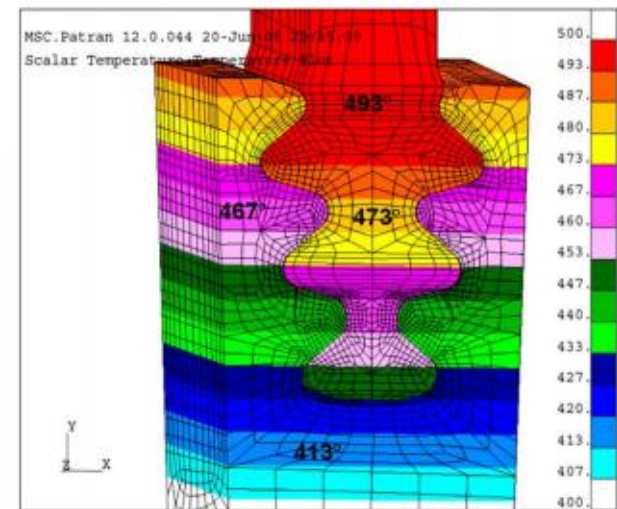
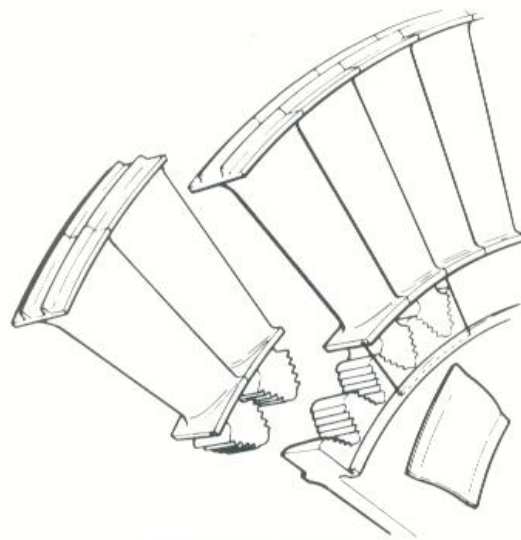


Fig. 6. Thermal field defined for models of disc and blade in the dovetail-rim region (Celsius scale).

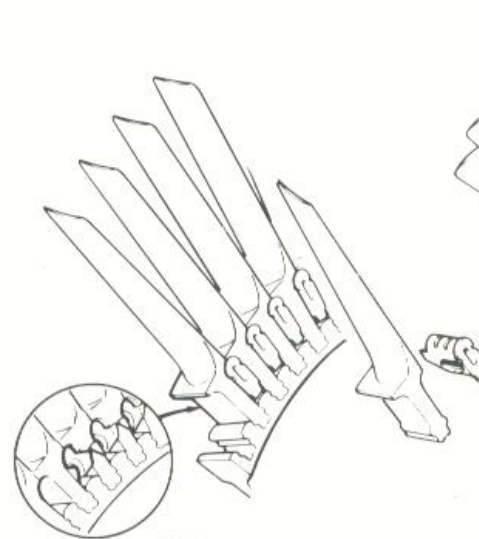
L. Witek / Engineering Failure Analysis 13 (2006) 9–17



Fig. 2. View of the fractured disc.



FIR TREE ROOT
(with locking plate)



FIR TREE ROOT
(with shank seals)



DE LAVAL BULB ROOT
(with locking screw)



B.M.W. HOLLOW BLADE
(with retaining pins)

Fig. 5-9 Various methods of attaching blades to turbine discs.

Turbine Blades

- ✱ The blades while glowing red hot must be strong enough to carry the centrifugal loads. The blades must also be resistant to fatigue and thermal shock. They must also be resistant to corrosion and oxidization.
- ✱ Nickel based alloys are used, investment casting can be controlled to produce single crystal or direction crystals that form columns in the blade.
- ✱ Non-metal blades can be produced from reinforced ceramics. These are used for small high speed turbines that have high entry temperatures.

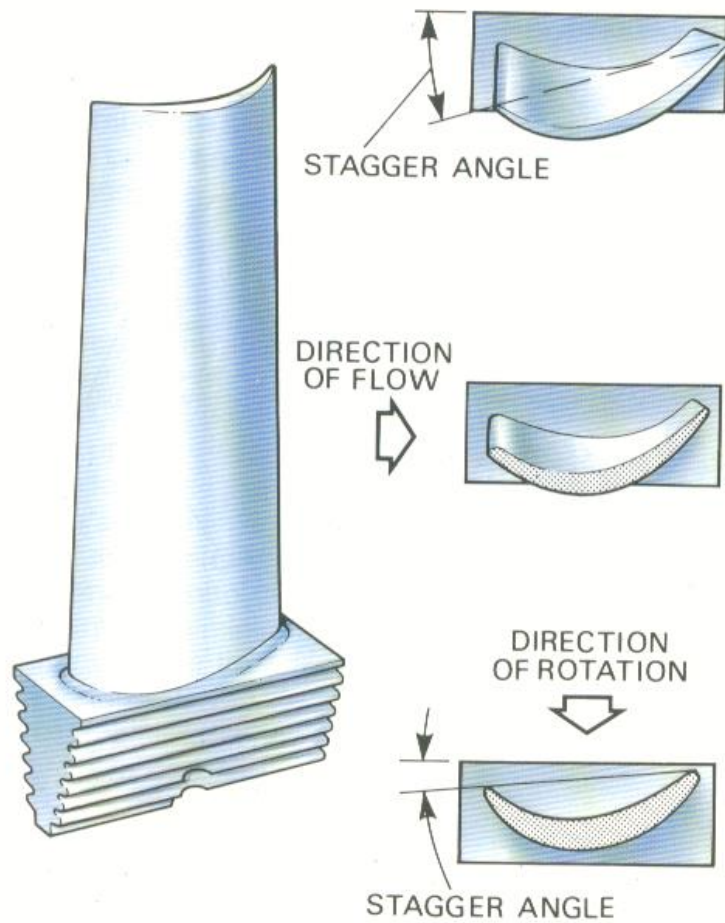


Fig. 5-6 A typical turbine blade showing twisted contour.

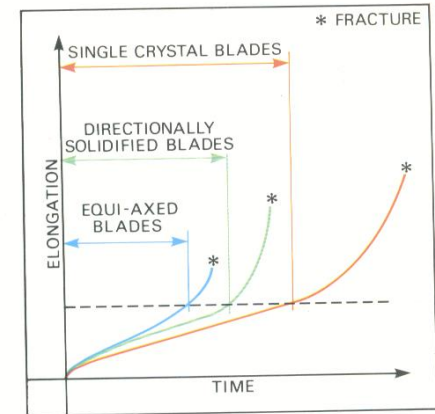
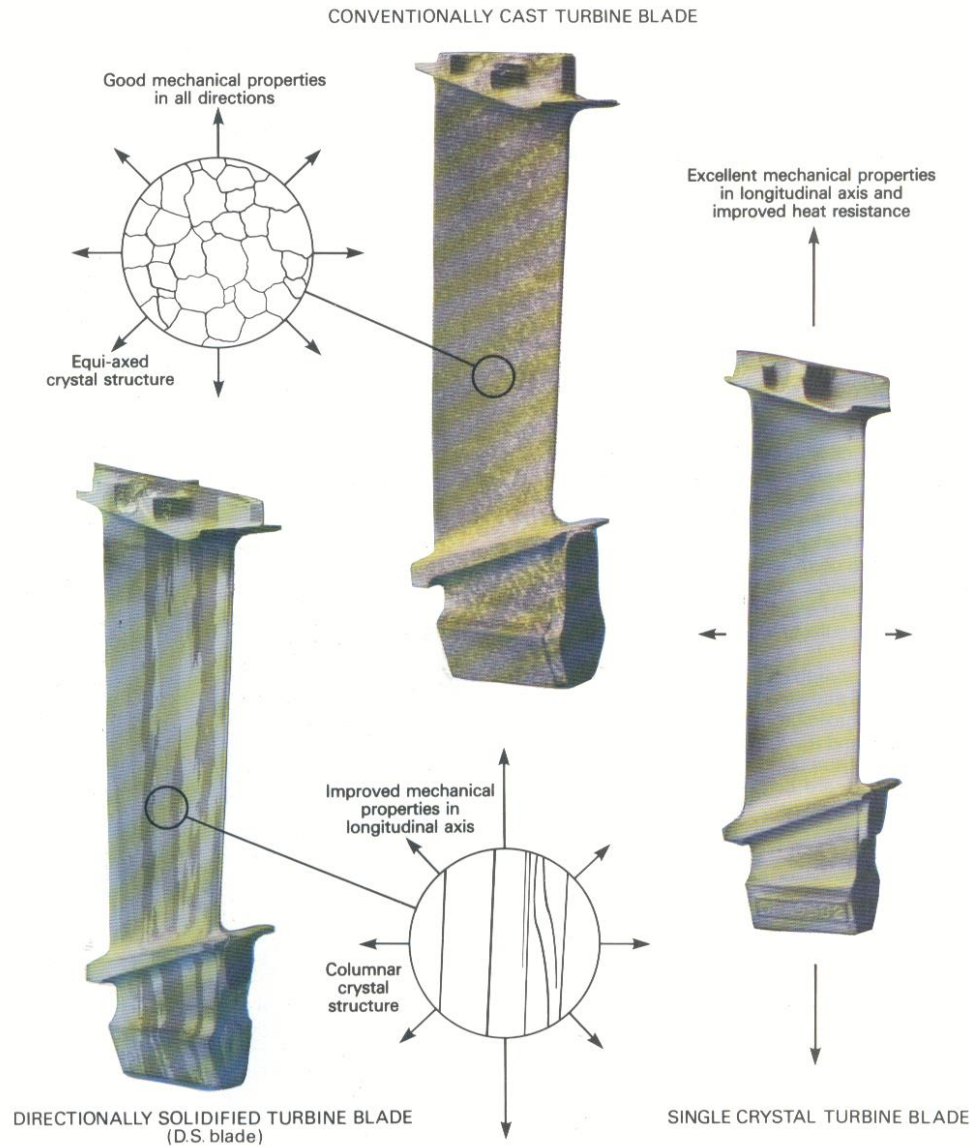


Fig. 5-13 Comparison of turbine blade life properties.

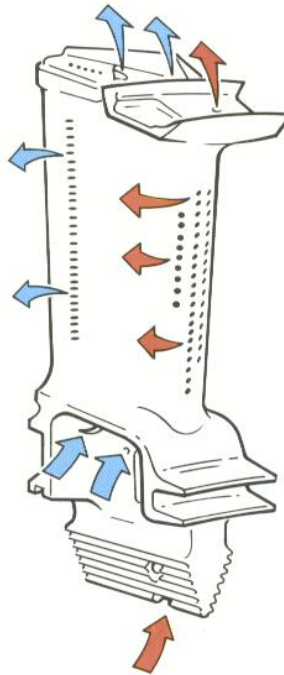


Fig. 5-14 Ceramic turbine blades.

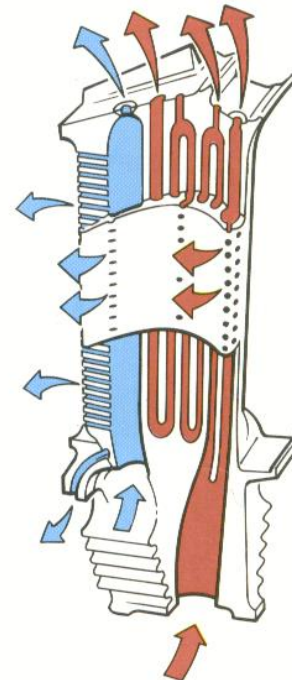
■ L.P. cooling air ■ H.P. cooling air



SINGLE PASS,
INTERNAL COOLING
(1960's)



SINGLE PASS,
MULTI-FEED
INTERNAL COOLING
WITH FILM COOLING
(1970's)



QUINTUPLE PASS,
MULTI-FEED
INTERNAL COOLING
WITH EXTENSIVE
FILM COOLING

Fig. 9-3 Development of high pressure turbine blade cooling.

Superalloys

- ☀ Superalloys are special heat resisting alloys that are used primarily above 550°C.
- ☀ The major constituent is either nickel or cobalt, or a combination of iron and nickel, and percentages of alloying elements is often quite large.
- ☀ For example, the Nickel based alloy Udimet 500 contains 48% Ni, 19% Cr and 19% Co; and the Cobalt based alloy Haynes 188 has 37% Co, 22% Cr, 22% nickel and 14% W, with both containing small percentages of other elements.
- ☀ Other superalloys are Waspaloy, MAR-M302, A286 and Inconel 718

Superalloys

- ✱ Although nickel and cobalt have melting temperatures just below that of iron, super alloys have superior resistance to corrosion, oxidation and creep compared with steels.
- ✱ Many have substantial strengths even above 750°C, which is beyond the useful ranges for low-alloy and stainless steels.
- ✱ This accounts for their use in high-temperature applications, despite the high cost due to the relative scarcity of nickel, chromium and cobalt.
- ✱ Superalloys are often produced in wrought form, and Ni-base and Co-base alloys are also often cast; they are challenging to machine.
- ✱ Strengthening is primarily by solid solution effects and by various heat treatments, resulting in precipitation of intermetallic compounds or metal carbides

Exhaust System

- ✱ Must withstand high gas temperatures and is hence manufactured from nickel or titanium
- ✱ To prevent heat being transferred to the surrounding aircraft structure air is passed around the jetpipe
- ✱ With afterburners the jet pipe is of double wall construction with an annular space between the walls. The hot gases leaving the propelling nozzle induce, by ejector action, a flow of air through the annular space of the engine nacelle. This flow cools the inner wall of the jetpipe.
- ✱ Must allow expansion and contraction without damage

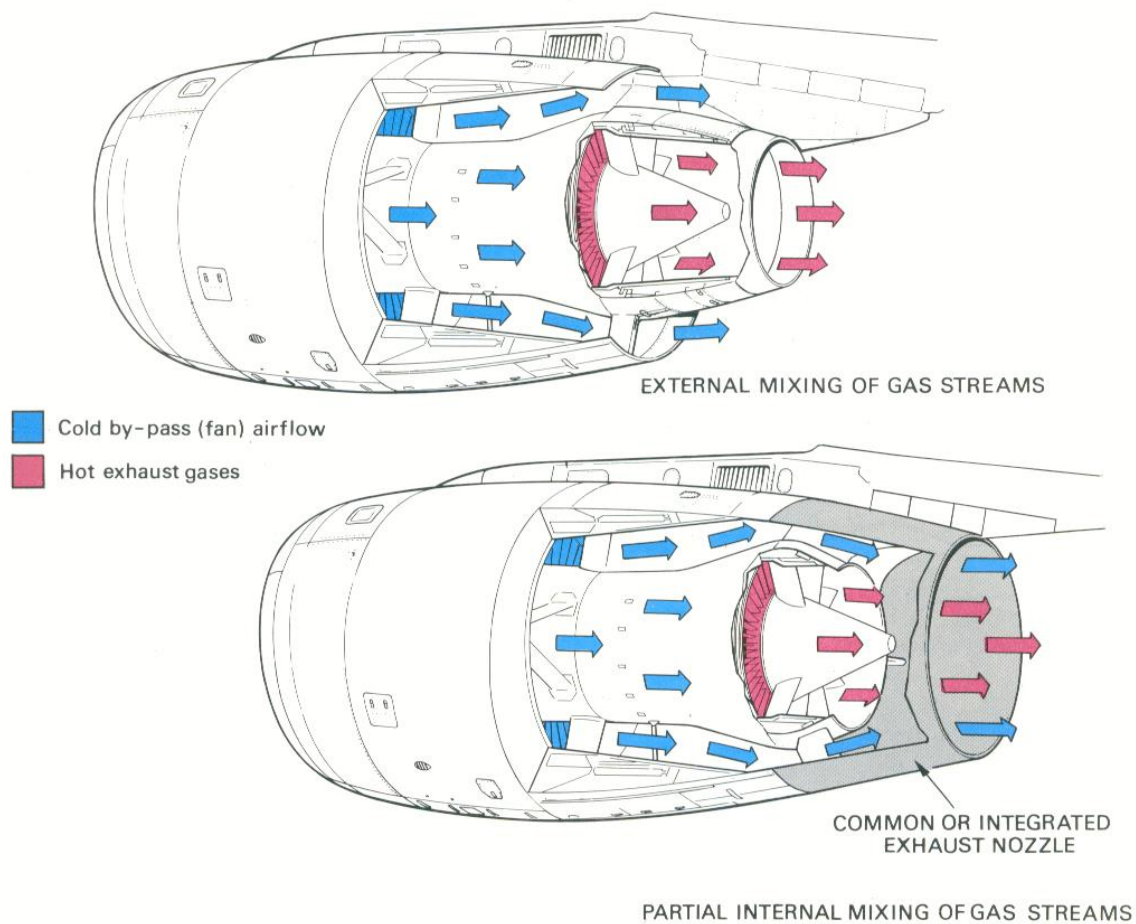


Fig. 6-5 High by-pass ratio engine exhaust systems.

Air Crash Investigation of Qantas 32 Airbus A380

<https://www.youtube.com/watch?v=f7FkTKQ-QRY>

- ✦ Its interesting to watch the whole video but going to minute 35 of the video will save you time



<https://www.youtube.com/watch?v=7ITgMXtuMv0> stainless steel tube making - seamless - not linked to this accident but showing tube manufacture

Manufacturing a gas Turbine Rolls Royce

https://www.youtube.com/watch?v=Vfo_mloUg2Gw Part 1

<https://www.youtube.com/watch?v=s6q1M-gvzPY> Part 2 and 3 blades

<https://www.youtube.com/watch?v=E0jCXSVGHYU> Part 4

Manufacture

- ✱ Engine components are produced from a variety of high tensile steel and high temperature nickel and cobalt alloy forgings.
- ✱ A proportion of components are cast using the investment casting process
- ✱ Fabrications, which form an increasing content, are produced from materials such as stainless steel, titanium and nickel alloys using modern joining techniques ie:
 - ✱ tungsten inert gas welding, resistance welding, electron beam welding and high temperature brazing in vacuum furnaces.

Manufacture

- ✱ The methods of machining engine components include:
 - ✱ Grinding, turning, drilling, boring and broaching whenever possible
- ✱ With more difficult materials and configurations being machined by:
 - ✱ Electro discharge, electro chemical, laser hole drilling and chemical size reduction.
- ✱ Structural components ie: cold spoiler, location rings, and by-pass ducts, benefit by considerable weight savings when using composite materials.

Manufacture

- ✱ Chemical and thermal processes are used on part finished and finished components, these include:
 - ✱ Heat treatment, electro-plating, chromate sealing, chemical treatments, anodizing to prevent corrosion, chemical and mechanical cleaning, wet and dry abrasive blasting, polishing, plasma spraying, electrolytic etching, and polishing to reveal metallurgical defects
 - Barrelling techniques for removal of burrs and surface improvement
- ✱ Most processes are concerned with surface changes, some give resistance to corrosion whilst others are used to relieve unwanted stress

TABLE 26.1 General Characteristics of Advanced Machining Processes

Process	Characteristics	Process parameters and typical material removal rate or cutting speed
Chemical machining (CM)	Shallow removal (up to 12 mm) on large flat or curved surfaces; blanking of thin sheets; low tooling and equipment cost; suitable for low production runs.	0.0025–0.1 mm/min.
Electrochemical machining (ECM)	Complex shapes with deep cavities; highest rate of material removal among nontraditional processes; expensive tooling and equipment; high power consumption; medium to high production quantity.	V: 5–25 dc; A: 1.5–8 A/mm ² ; 2.5–12 mm/min, depending on current density.
Electrochemical grinding (ECG)	Cutting off and sharpening hard materials, such as tungsten-carbide tools; also used as a honing process; higher removal rate than grinding.	A: 1–3 A/mm ² ; Typically 25 mm ³ /s per 1000 A.
Electrical-discharge machining (EDM)	Shaping and cutting complex parts made of hard materials; some surface damage may result; also used as a grinding and cutting process; expensive tooling and equipment.	V: 50–380; A: 0.1–500; Typically 300 mm ³ /min.
Wire EDM	Contour cutting of flat or curved surfaces; expensive equipment.	Varies with material and thickness.
Laser-beam machining (LBM)	Cutting and holmaking on thin materials; heat-affected zone; does not require a vacuum; expensive equipment; consumes much energy.	0.50–7.5 m/min.
Electron-beam machining (EBM)	Cutting and holmaking on thin materials; very small holes and slots; heat-affected zone; requires a vacuum; expensive equipment.	1–2 mm ³ /min.
Water-jet machining (WJM)	Cutting all types of nonmetallic materials to 25 mm and greater in thickness; suitable for contour cutting of flexible materials; no thermal damage; noisy.	Varies considerably with material.
Abrasive water-jet machining (AWJM)	Single or multilayer cutting of metallic and nonmetallic materials.	Up to 7.5 m/min.
Abrasive-jet machining (AJM)	Cutting, slotting, deburring, deflashing, etching, and cleaning of metallic and nonmetallic materials; manually controlled; tends to round off sharp edges; hazardous.	Varies considerably with material.

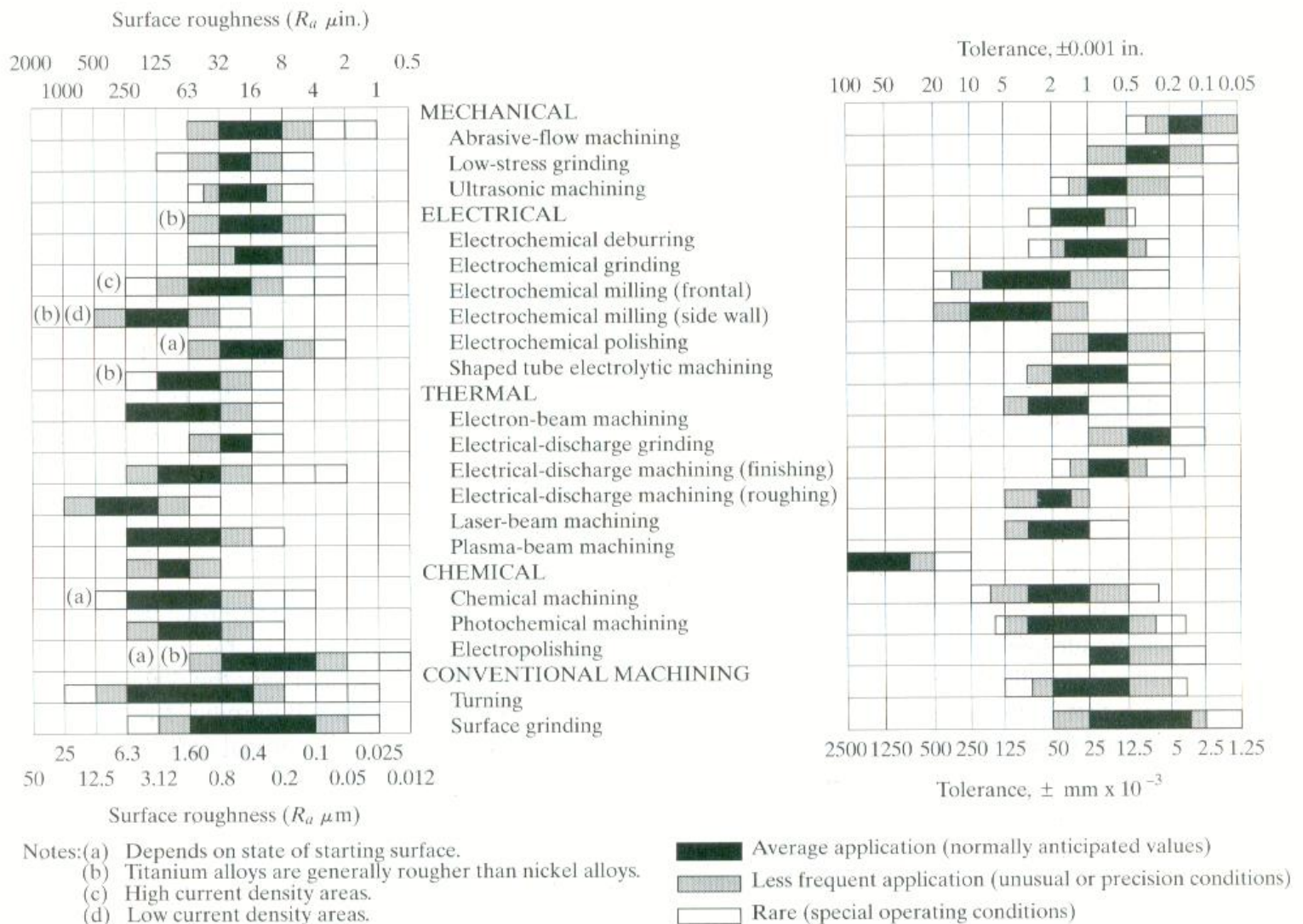


FIGURE 26.4 Surface roughness and tolerances obtained in various machining processes. Note the wide range within each process (see also Fig. 22.13). *Source: Machining Data Handbook, 3rd ed. Copyright © 1980. Used by permission of Metcut Research Associates, Inc.*

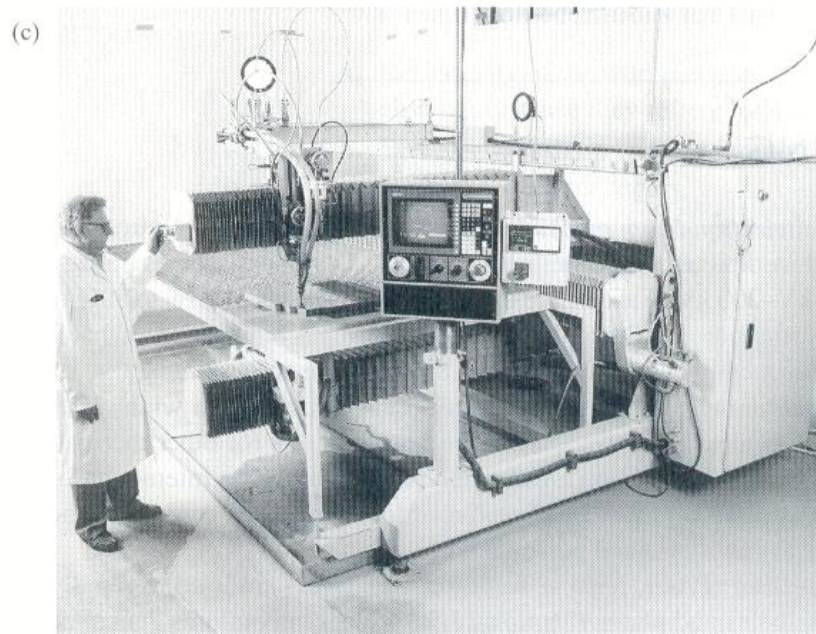
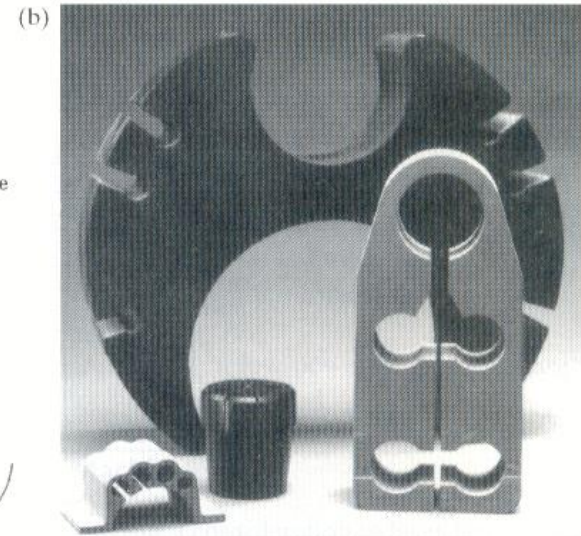
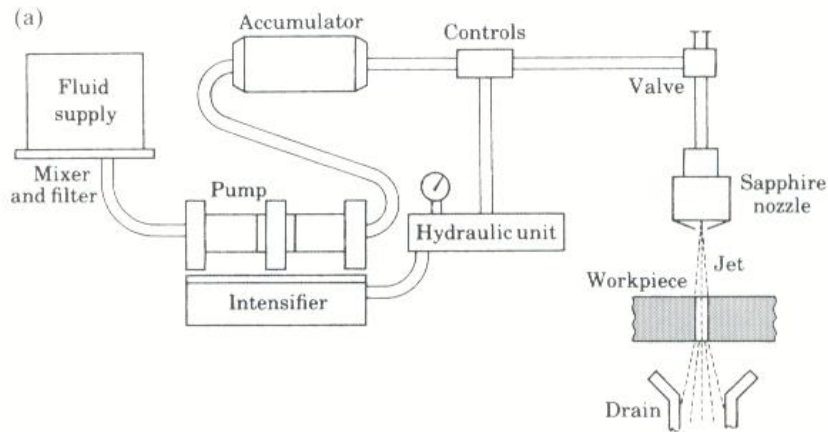
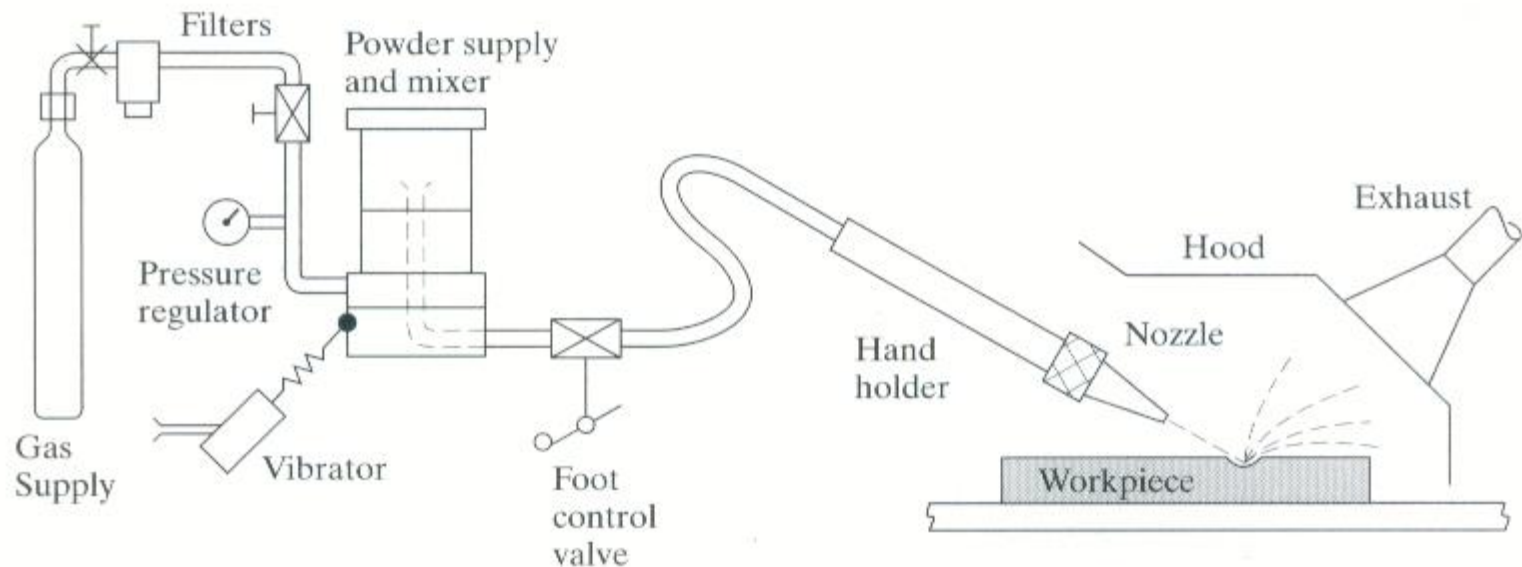


FIGURE 26.16 (a) Schematic illustration of water-jet machining. (b) A computer-controlled, water-jet cutting machine cutting a granite plate. (c) Example of various nonmetallic parts produced by the water-jet cutting process. *Source:* Courtesy of Possis Corporation.

<http://www.flowcorp.com/waterjet-resources.cfm?id=360>

FLOW company website

FIGURE 26.17 Schematic illustration of the abrasive-jet machining process.



<https://www.youtube.com/watch?v=PZFPxvMGEWs&list=UUVLcPpvBTYrUsCY8aFdQSkA&index=2&feature=plc>
water jet cutting

Manufacture

- ✱ The main structure of an aero gas turbine engine is formed from a number of circular castings, which are assembled and secured together by flanged joints and couplings located with dowels and tenons.

Manufacture

- ★ Automation is applied in the manufacture of cast turbine blades in cells with computer numerical control (CNC) grinding centres, laser hard-facing and film cooling hole drilling by electro-discharge machining (EDM)
- ★ Families of turbine and compressor discs are produced in flexible manufacturing cells, employing automated guided vehicles delivering palletised components from computerized storage to CNC machining cells that use batch of one techniques
- ★ The smaller blades with very thin airfoil sections are produced by integrated broaching and 360 degree electro-chemical machining (ECM)

<http://www.youtube.com/watch?v=sbH8fko7uXA&feature=fvst>

Broaching

Manufacture

- ✱ Computer Aided Design (CAD) and Computer Aided Manufacture (CAM) provides an equivalent link when engine components designed by CAD can be used for the preparation of manufacturing drawings, programmes for CNC machines, tool layouts, tool designs, operation sequence, estimating and scheduling.
- ✱ Computer simulation allows potential cell and flow line manufacture to be proven before physical machine purchase and operation

Volkswagen CIM plant

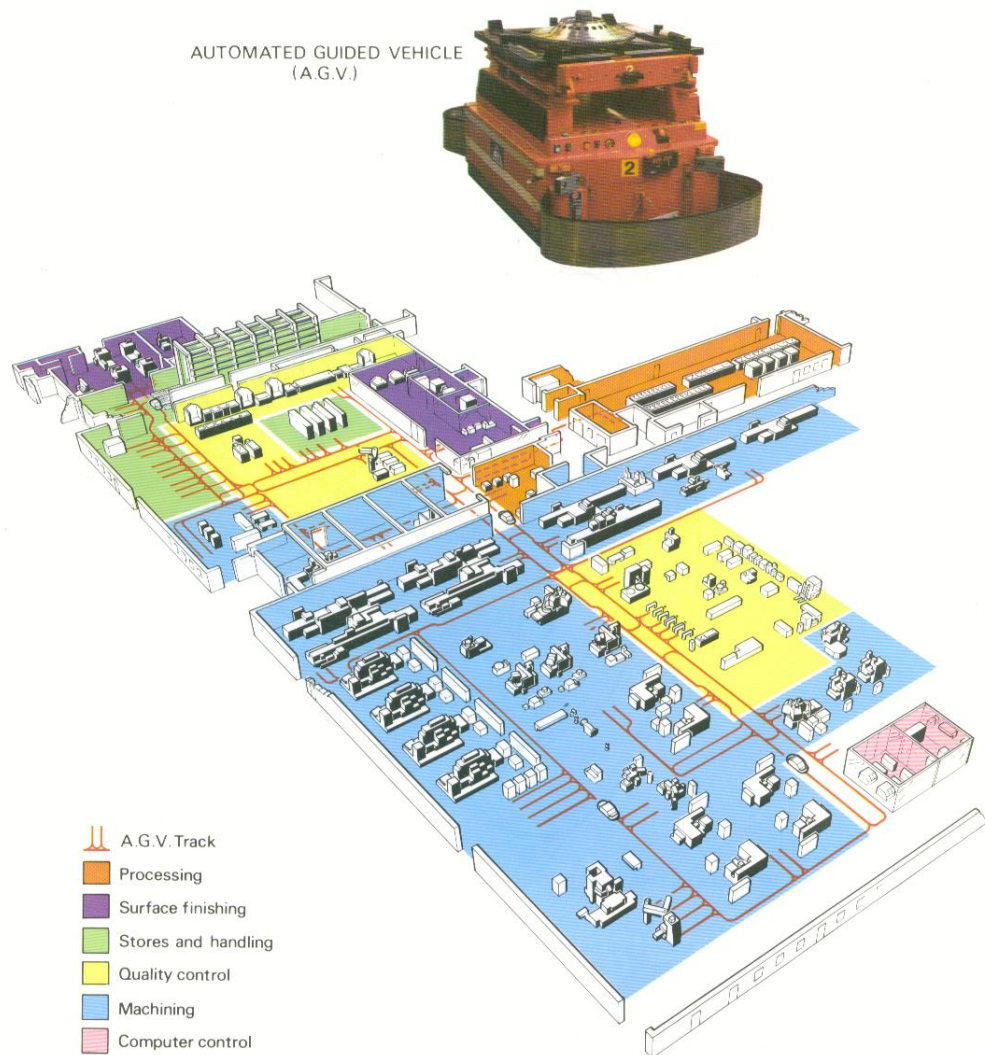


Fig. 22-15 Advanced integrated manufacturing system (A.I.M.S.).

without further operator intervention. In the chip machining (i.e., turning, boring, milling etc.) and metal forming processes C.N.C. machine tools enable consistency of manufacture which can be statistically inspected i.e., one in ten. Component integrity is

achieved by use of ultrasonic, radiological, magnetic particle and penetrant inspection techniques, as well as electrolytic and acid etching to ensure all material properties are maintained to both laboratory and quality acceptance standards.

Forging

<https://www.youtube.com/watch?v=Qh9nvoRicKc> Titanium compressor blade forging

- ✱ Engine drive shafts, compressor discs and blades, turbine discs and blades, and gear trains are forged to near optimum shape as is possible.
- ✱ Forging calls for a very close control of the temperature during the various operations, a high standard of furnace control is required.
- ✱ Annular combustion rings can be cold forged to exacting tolerances without further machining before being welded together to produce the combustion casing.
- ✱ HP compressor casings are forged as rings or half rings, which when assembled together, form the rigid structure of the engine. Stainless steel, titanium and nickel alloys.

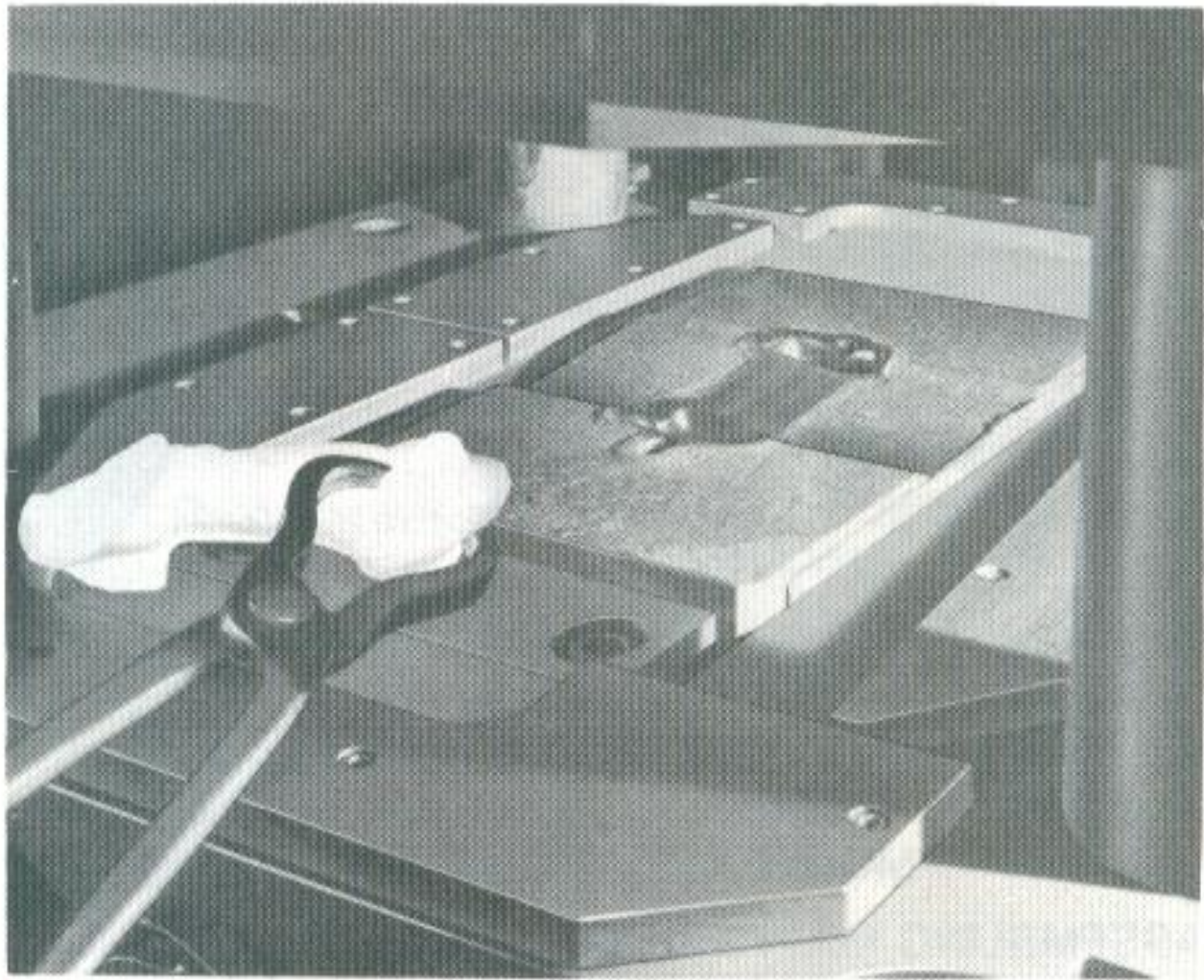


Fig. 22-2 Precision forging.

Casting

- ✱ An increasing percentage of the gas turbine engine is produced from cast components using sand casting, die casting and investment casting techniques
- ✱ Investment casting becoming the foremost in use because of its capability to produce components with surfaces that require no further machining.
- ✱ In pursuit of ever increasing performance, turbine blades are produced from high temperature nickel alloys that are cast by the investment casting or “lost wax” technique.
- ✱ Directionally solidified and single crystal turbine blades are cast using this technique in order to extend their cyclic lives.

<http://www.youtube.com/watch?v=BX8w-GUPz1w> investment casting

Investment Casting

- ★ Figure 22.4 illustrates automatic casting used in the production of equi-axed, directional solidified and single crystal blades
- ★ The lost wax process is unparalleled in its ability to provide the highest standards of surface finish, repeatable accuracy and surface detail in a cast component.
- ★ The increasing demands of the engine has manifested itself in the need to limit grain boundaries and provide complex internal passages

Single Crystal Blade Background Material

- ★ <https://www.youtube.com/watch?v=2xjhK2aSV1E> metal crystals
- ★ <https://www.youtube.com/watch?v=hOv2pGEruGk> not single crystal blade investment casting
- ★ <https://www.youtube.com/watch?v=br9iaeYYxSM&index=9&list=PLj4YiOgq320rn6VzRpirTPWnssZTr20D3> single crystal blade simulation

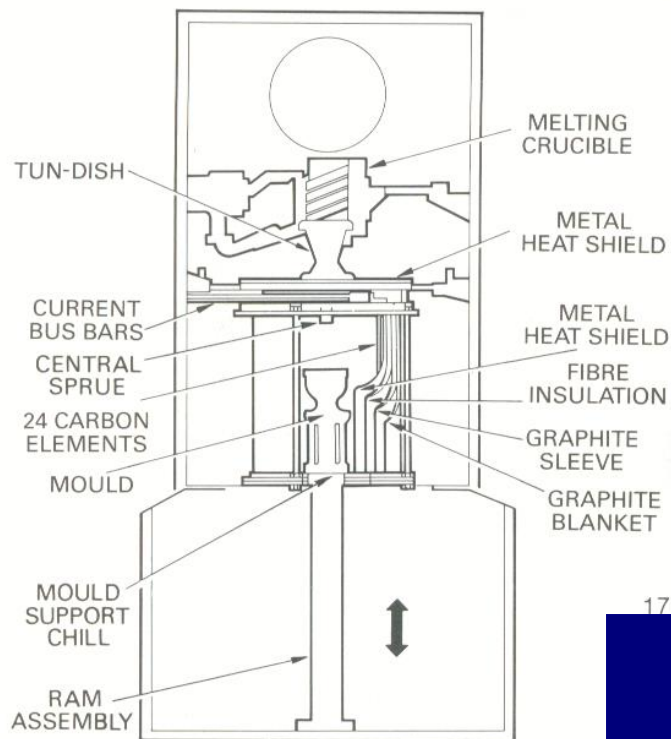
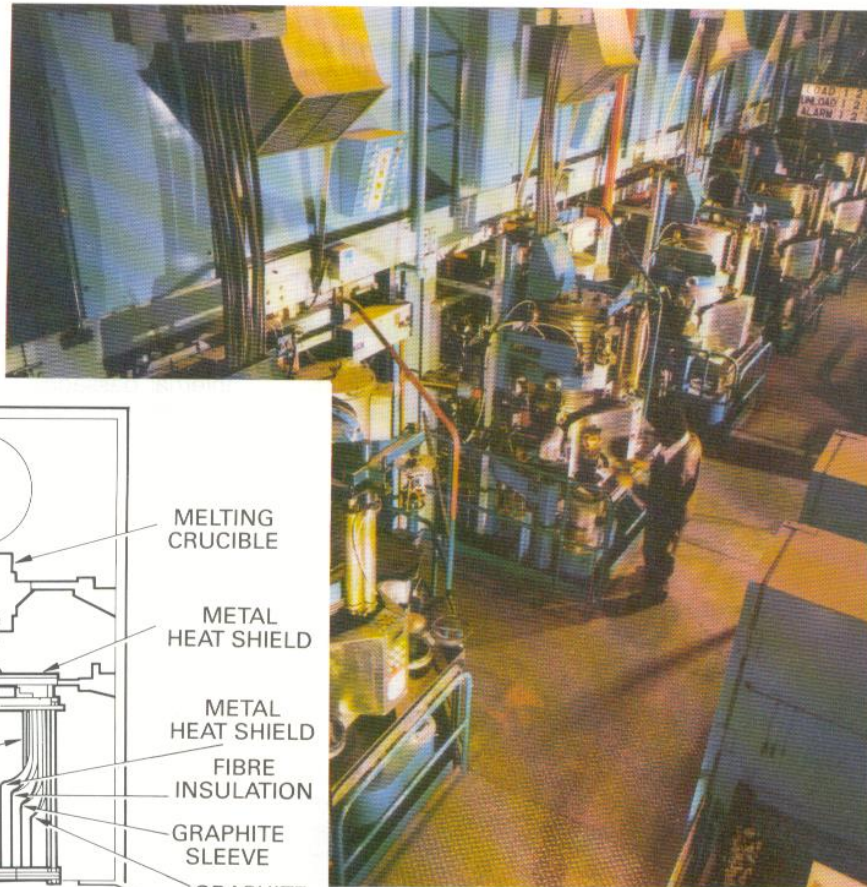


Fig. 22-4 Automatic investment casting.



17. Forging calls for a very close control of the

<https://www.youtube.com/watch?v=lvvjUsS-Jno> turbine blades 2.00 min

Investment Casting

- ★ The moulds used for directional solidified and single crystal castings differ from conventional moulds in that they are open at both ends.
- ★ The base of a mould forms a socketed bayonet fitting into which a chill plate is located during casting.
- ★ Metal is introduced from the central sprue into the mould cavities via a ceramic filter.
- ★ These and oriented seed crystals, if required, are assembled with the patterns prior to investment.

Investment Casting

- ✦ Extensive automation is possible to ensure the wax patterns are coated with the shell material consistently by using robots.
- ✦ The final casting can also have their rises removed using elastic cut-off wheels driven by robot arms. Figure 22-5

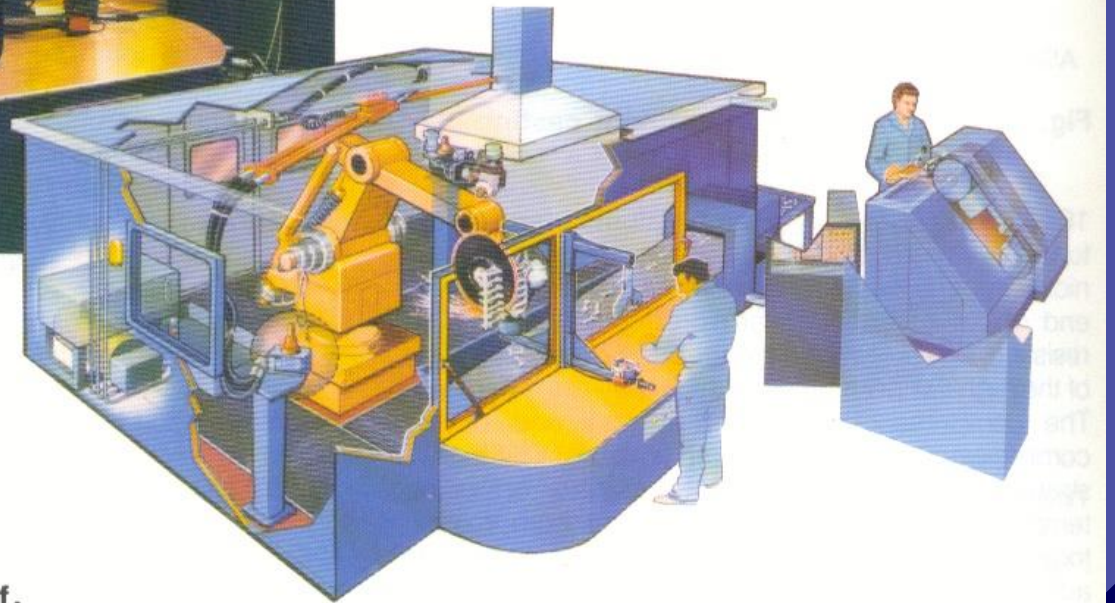


Fig. 22-5 **Robot cut-off.**

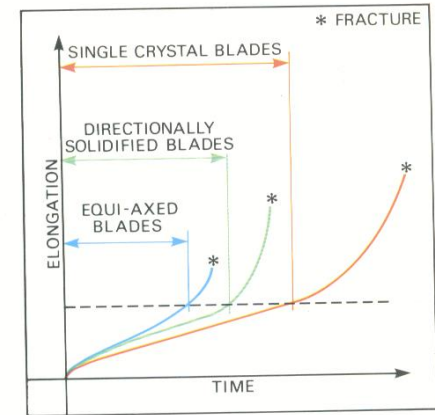
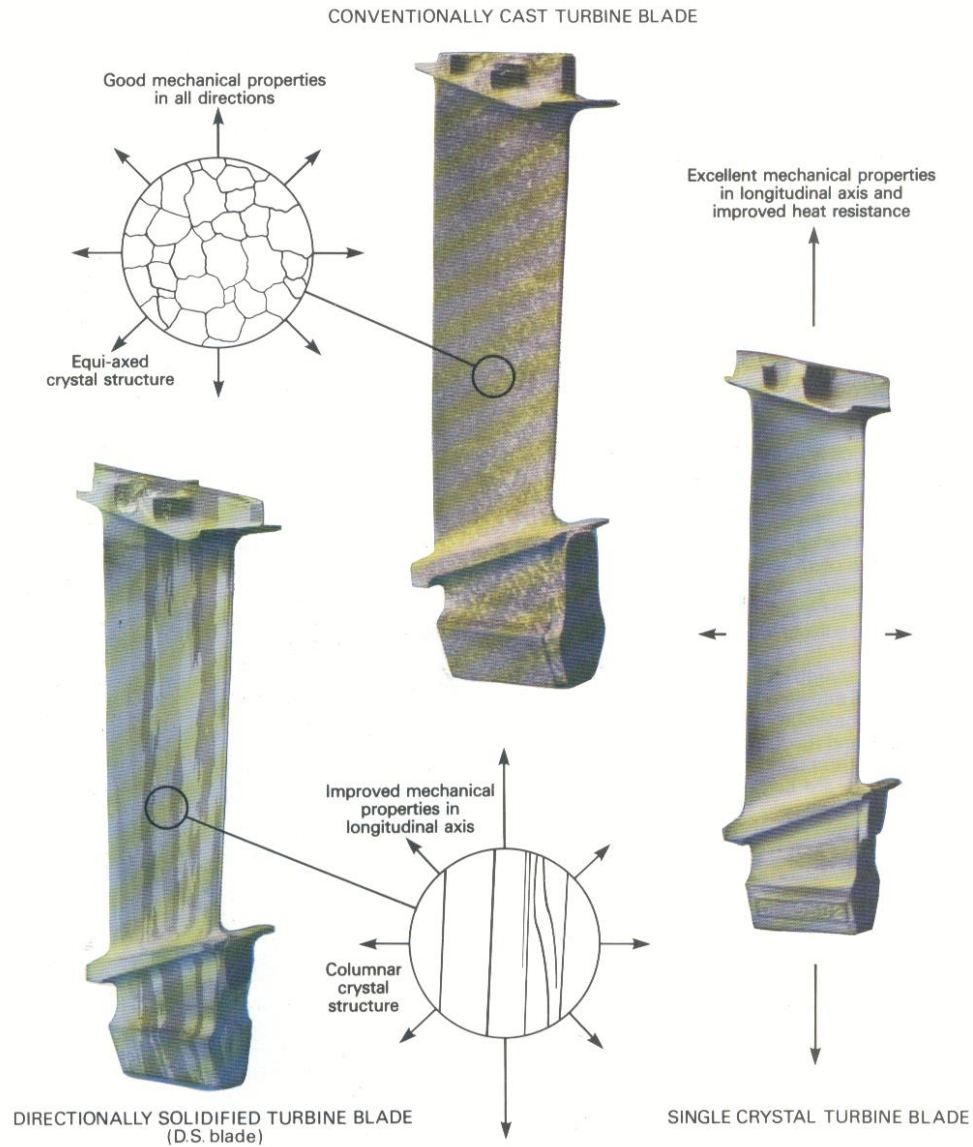


Fig. 5-13 Comparison of turbine blade life properties.

Fabrication

- ★ Major components of the gas turbine:
 - ★ Bearing housings, combustion and turbine casings, exhaust units, jet pipes, by-pass mixer units, low pressure compressor casings
- ★ Can be produced as fabricated assemblies using sheet materials such as:
 - ★ Stainless steel, titanium, varying types of nickel alloys

Titanium Alloys

- ✱ The density of titanium is considerably greater than aluminium, but still only about 60% of that of steel.
- ✱ In addition the melting temperature is somewhat greater than for steel and far greater than for aluminium.
- ✱ In aerospace applications, the strength to weight ratio is important, and in this respect the highest strength titanium alloys are comparable to the highest strength steels.
- ✱ These characteristics and good corrosion resistance have led to an increase in the application of titanium alloys.

Titanium Alloys

- Three categories exist: the alpha and near alpha alloys, the beta alloys and the alpha-beta alloys.
- Although the alpha (HCP) crystal structure is stable at room temperature in pure titanium, certain combinations of alloying elements, such as chromium along with vanadium, cause the beta (BCC) structure to be stable, or they result in a mixed structure.
- Small percentages of molybdenum or nickel improve corrosion resistance; aluminium, tin and zirconium improve creep resistance of the alpha phase.
- Alpha alloys are strengthened mainly by solid solution effects and do not respond to heat treatment. The other alloys respond to heat treatment.
- Precipitation hardening and the effects of complex multi phases are the principle means of strengthening alpha-beta and beta alloys.

Fabrication of Titanium Fan Blades

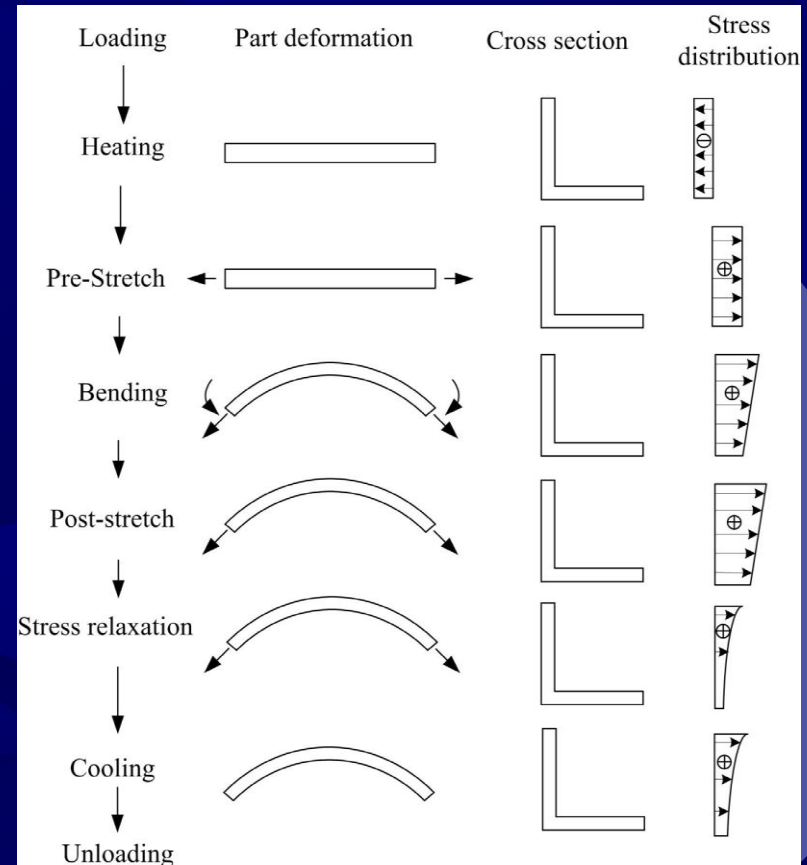
- ✱ The low pressure compressor wide chord fan blade comprise rolled titanium side panels assembled in dies, hot twisted in a furnace and finally hot creep formed to achieve the necessary configuration.
 - ✱ Chemical milling is used to recess the centre of each panel which sandwiches a titanium honeycomb core.
 - ✱ Both panels and the honeycomb are finally joined together using automated furnaces where an activated diffusion bonding takes place.
- Figure 22-6

Hot stretch bending and creep forming process

- Hot stretch bending and creep forming process is used to reduce springback in forming titanium alloy profile. The forming cycle is shown in the Figure opposite
- The principle of hot stretch bending and creep forming is leading a stress relaxation stage by maintaining the workpiece against the die for a selected dwell time (2400 s) after the hot stretch bending stage.
- At the same time the temperature is controlled as needed. This allows the benefits of low residual stress and minimum springback, moreover, inexpensive tooling and good repeatability

1792 – 1798]

[Procedia Engineering 81 (2014)



Diffusion bonding

- ★ Diffusion bonding is a solid-state joining process capable of joining a wide range of metal and ceramic combinations to produce both small and large components.
- ★ The process is dependent on a number of parameters, in particular: time, applied pressure, bonding temperature and method of heat application.
- ★ Diffusion bonding can be categorised into a number of variants, dependent on the form of pressurisation, the use of interlayers and the formation of a transient liquid phase.

Diffusion bonding

- ✱ In its simplest form, diffusion bonding involves holding pre-machined components under load at an elevated temperature usually in a protective atmosphere or vacuum.
- ✱ The loads used are usually below those which would cause macrodeformation of the parent material(s) and temperatures of $0.5-0.8T_m$ (where T_m = melting point in K) are employed.
- ✱ Times at temperature can range from 1 to 60+ minutes, but this depends upon the materials being bonded, the joint properties required and the remaining bonding parameters.
- ✱ Although the majority of bonding operations are performed in vacuum or an inert gas atmosphere, certain bonds can be produced in air.

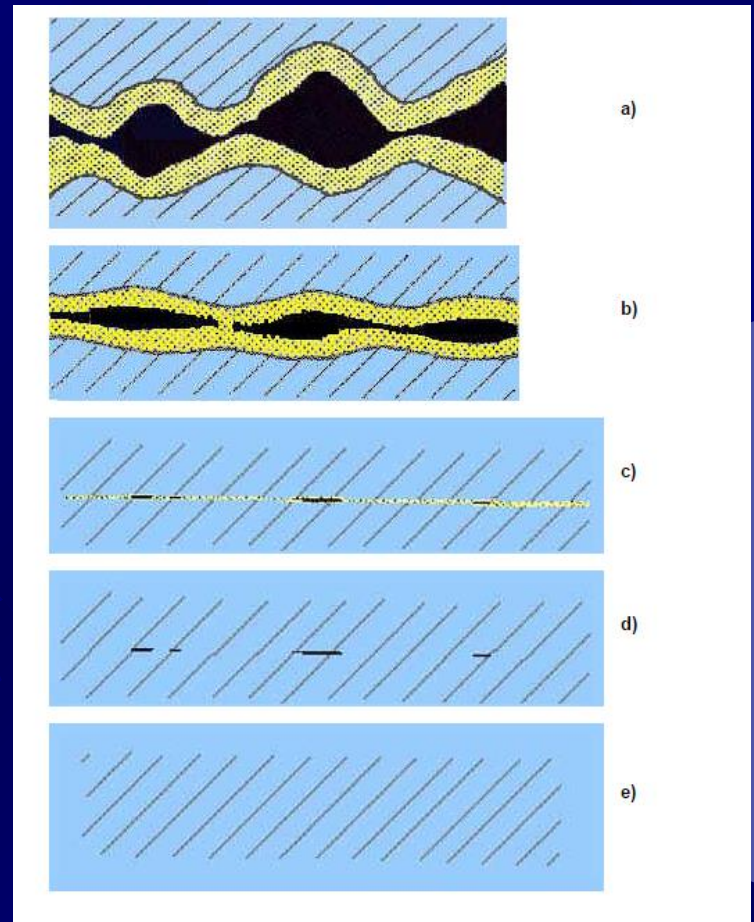
Diffusion bonding

- ★ To form a bond, it is necessary for two, clean and flat surfaces to come into atomic contact, with microasperities and surface layer contaminants being removed from the bonding faces during bonding.
- ★ Various models have been developed to provide an understanding of the mechanisms involved in forming a bond.
- ★ First they consider that the applied load causes plastic deformation of surface asperities reducing interfacial voids.
- ★ Bond development then continues by diffusion controlled mechanisms including grain boundary diffusion and power law creep.

Diffusion Bonding

The mechanism of diffusion bonding

- a) Initial 'point' contact, showing residual oxide contaminant layer
- b) Yielding and creep, leading to reduced voids and thinner contaminant layer
- c) Final yielding and creep, some voids remain with very thin contaminant layer
- d) Continued vacancy diffusion, eliminates oxide layer, leaving few small voids
- e) Bonding is complete.



Liquid Phase Diffusional Bonding

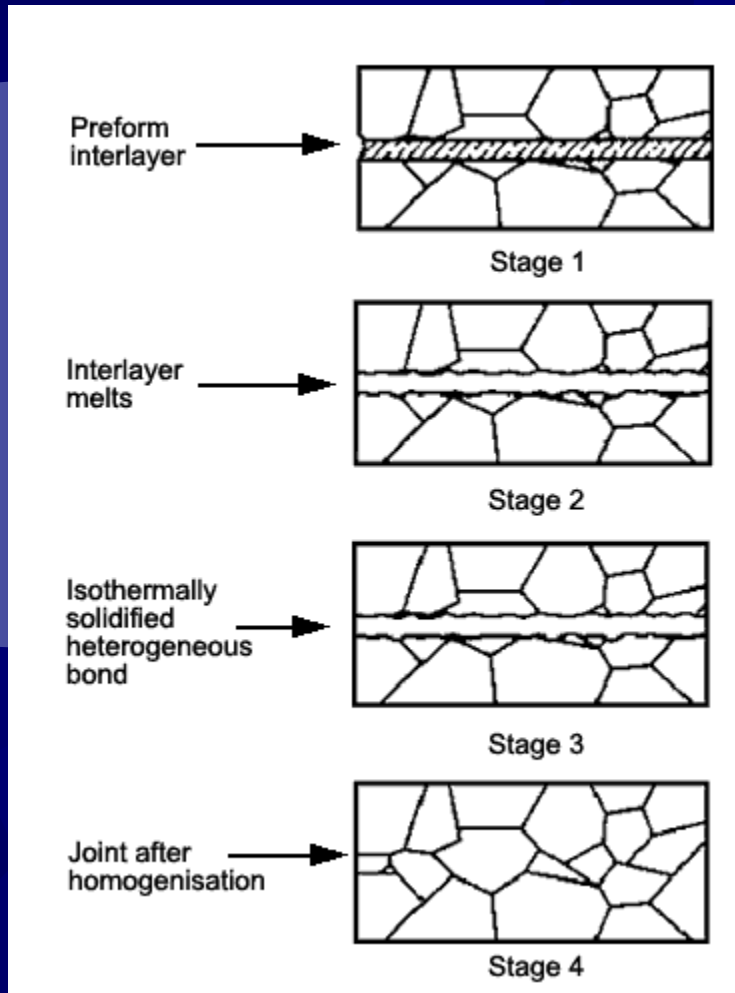
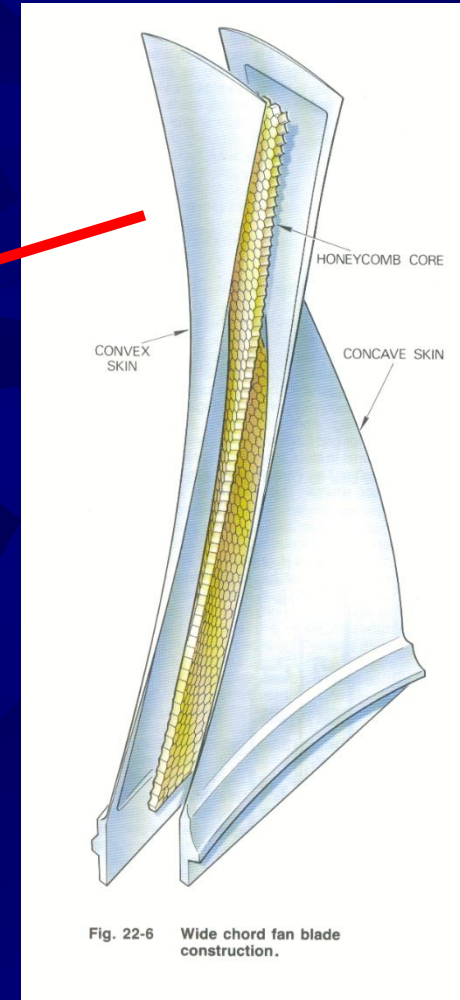
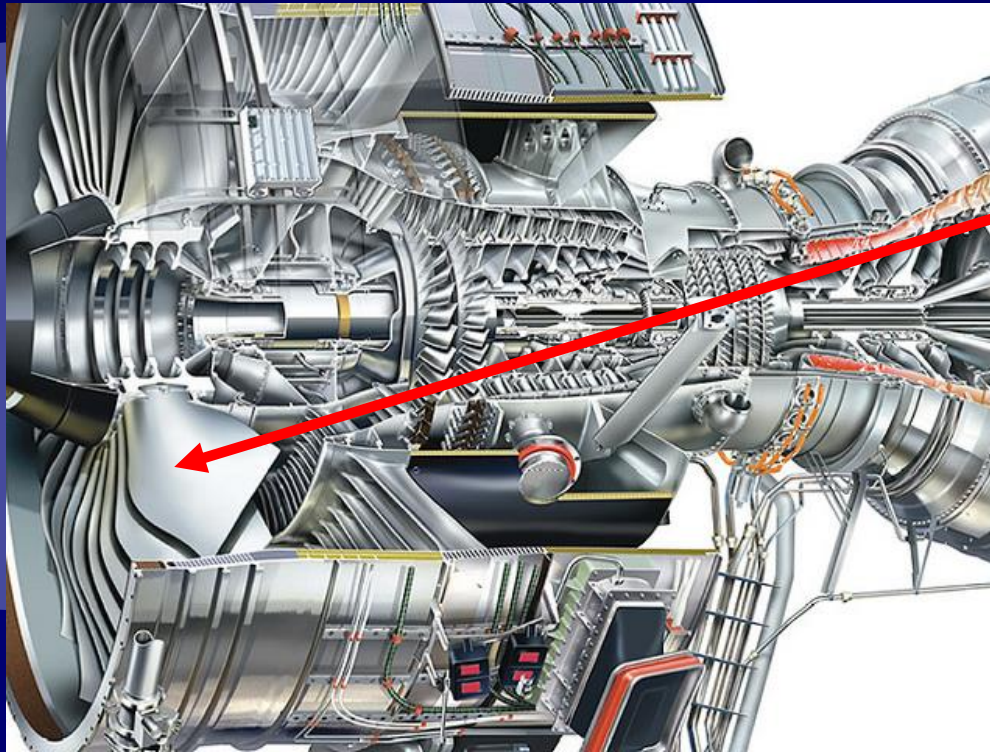


Fig.2 Schematic illustration of the steps involved in making a diffusion-brazed joint

- The dissimilar metal insert, melts at a lower temperature than the parent material. Thus a thin layer of liquid spreads along the interface to form a joint at a lower temperature than the melting point of either of the parent materials.
- A reduction in bonding temperature leads to solidification of the melt, and this phase can subsequently be diffused away into the parent materials by holding at temperature, *Fig.2*.

Titanium Fan Blade for Trent

XWB https://www.youtube.com/watch?v=IQYZHGSf_8E Diffusion Bonding

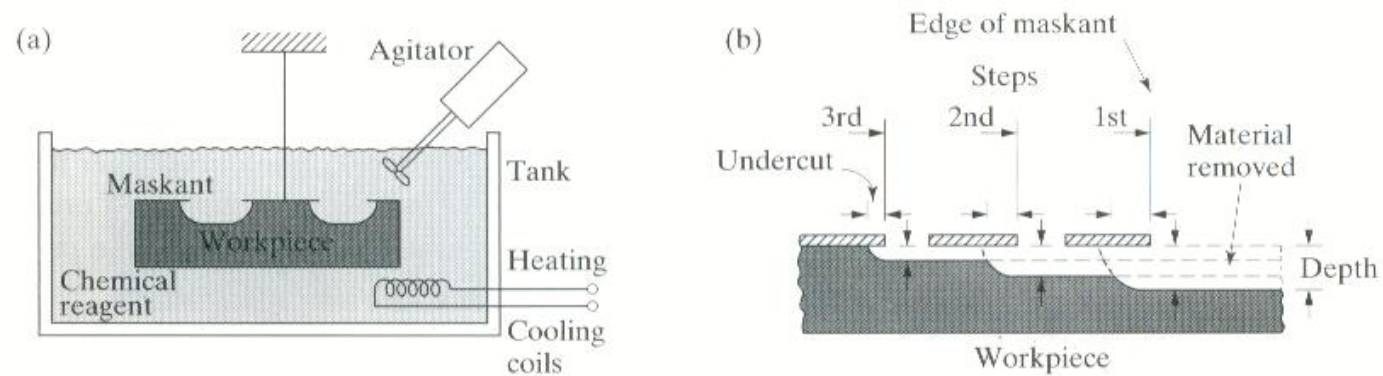


<https://www.youtube.com/watch?v=5EhMYMr834o> diffusion bonding

<https://www.youtube.com/watch?v=s6q1M-gvzPY> Blade 2.20 min

Chemical Milling

FIGURE 26.3 (a) Schematic illustration of the chemical machining process. Note that no forces or machine tools are involved in this process. (b) Stages in producing a profiled cavity by chemical machining; note the undercut.



<http://www.youtube.com/watch?v=jmVwu26i-Sk> Chemical milling

Chemical Milling

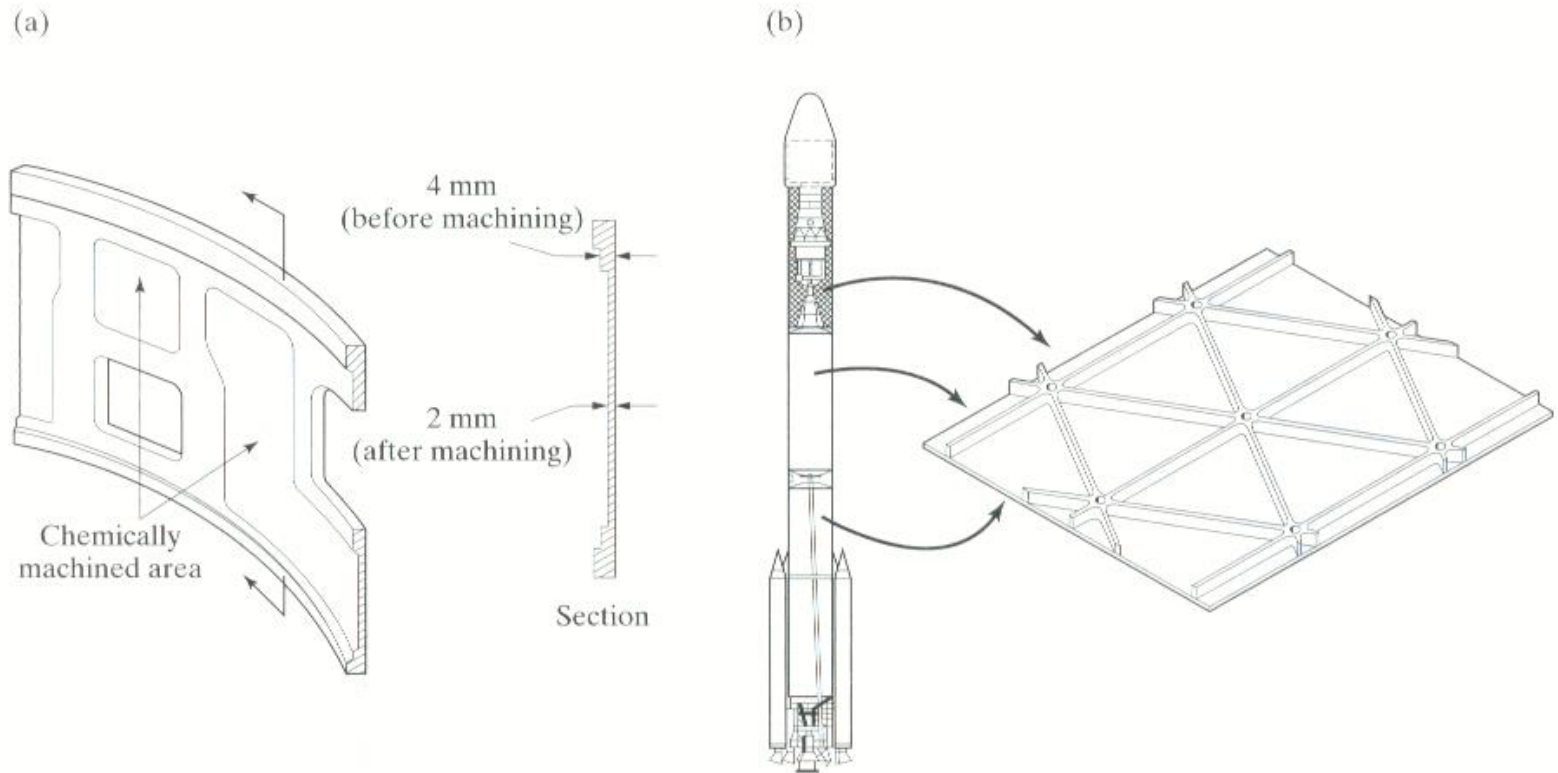


FIGURE 26.2 (a) Missile skin-panel section contoured by chemical milling to improve the stiffness-to-weight ratio of the part. (b) Weight reduction of space launch vehicles by chemical milling aluminum-alloy plates. These panels are chemically milled after the plates have first been formed into shape by processes such as roll forming or stretch forming. The design of the chemically machined rib patterns can be modified readily at minimal cost. *Source: Advanced Materials and Processes, December 1990. ASM International.*

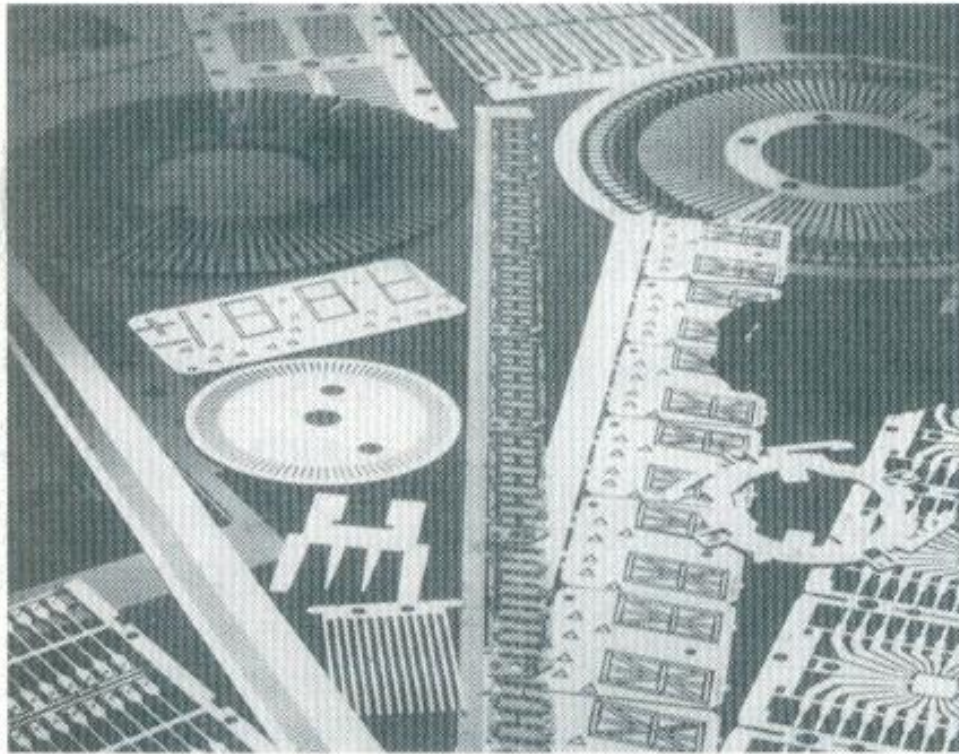


FIGURE 26.5 Various parts made by chemical blanking. Note the fine detail. *Source:* Courtesy of Buckbee-Mears St. Paul.

Welding

- ★ Welding processes are used extensively in the fabrication of gas turbine engine components, the most widely used are:
 - Resistance welding by **spot** and seam, tungsten inert gas, electron beam
- ★ Care must be taken to limit the distortion and shrinkage associated with these techniques

<http://www.youtube.com/watch?v=AwL1CAg43PU&NR=1&feature=fvwp>

spot welding

<https://www.youtube.com/watch?v=WSnj8AASuFs>

TIG welding

Welding

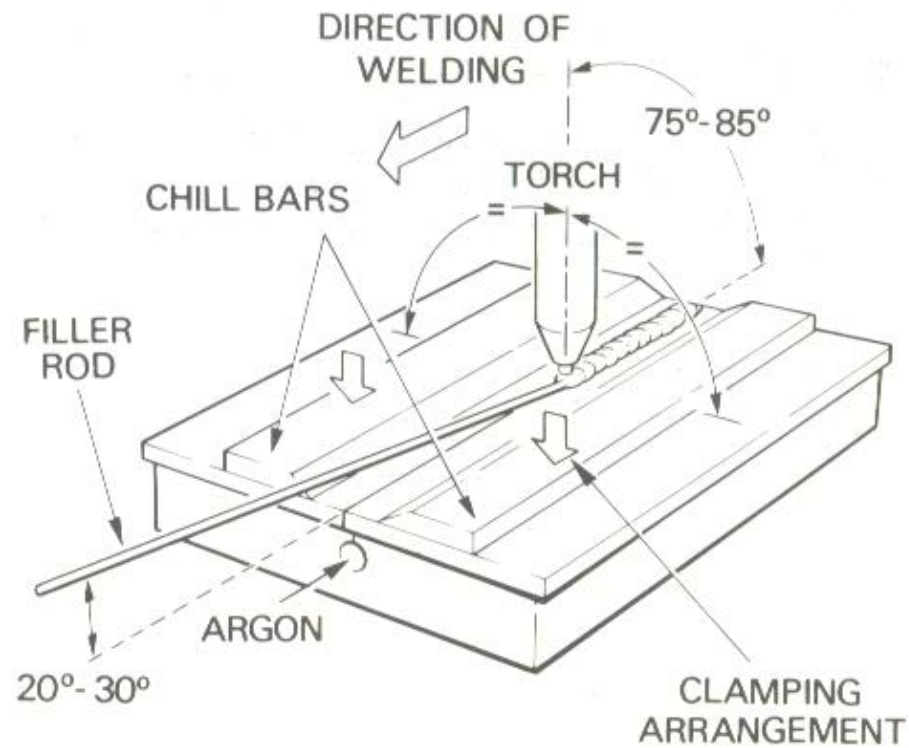


Fig. 22-7 Typical tungsten inert gas welding details.

TIG Welding

- ★ The most common form of TIG welding, fig. 22-7, in use is the direct current straight polarity, ie, negative pole.
- ★ This is the most economical method of producing high quality welds for the range of high strength/high temperature materials used in gas turbine engines
- ★ For this class of work, high purity argon shielding gas is fed to both sides of the weld and the welding torch nozzle is fitted with a gas lens to ensure maximum efficiency for shielding gas coverage.

TIG Welding

- ✱ A consumable 4% thoriated tungsten electrode, together with a suitable non-contact method of arc starting is used and the weld current is reduced in a controlled manner at the end of each weld to prevent the formation of finishing cracks.
- ✱ All welds are visually and penetrant inspected and in addition welds associated with rotating parts are radiologically examined.
- ✱ A typical TIG welding operation is shown in figure 22-8

Welding

<http://www.youtube.com/watch?v=YFhZMSV-yoQ> TIG welding



Fig. 22-8 Tungsten inert gas welding.

<http://www.youtube.com/watch?v=NONurFigP5I> E- beam welding

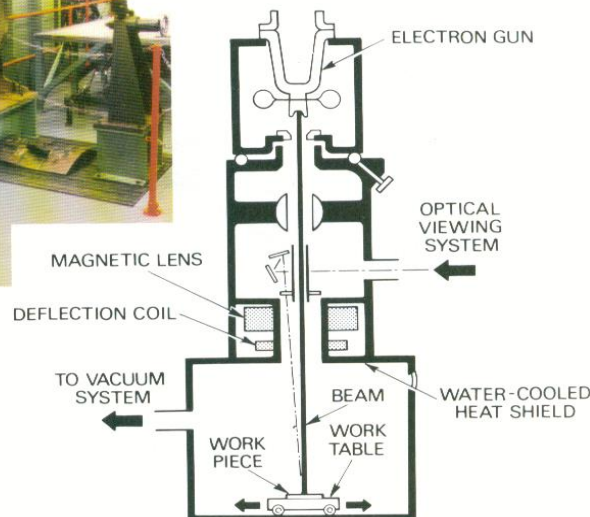


Fig. 22-9 Electron beam welding.

E-beam Welding

- ✴ This system can use either low or high voltage, uses a high power density beam of electrons to join a wide range of different materials and of varying thickness.
- ✴ The welding machine, figure 22-9, comprises:
 - ✴ An electron gun, optical viewing system, work chamber and handling equipment, vacuum pumping system, high or low voltage power supply, operating controls
- ✴ Many major rotating assemblies are manufactured as single items in steel, titanium and nickel alloys and joined together, ie, intermediate and high pressure compressor drums

E-beam Welding

- ✱ This technique allows design flexibility in that distortion and shrinkage are reduced and dissimilar materials, to serve quite different functions, can be homogeneously joined together.
- ✱ For example, the HP turbine stub shafts requiring a stable bearing steel welded to a material which can expand with the mating turbine disc.
- ✱ Automation has been enhanced by the application of CNC to the work handling and manipulation.
- ✱ Seam tracking to ensure that the joint is accurately followed and closed loop under-bead control to guarantee the full depth of material thickness is welded.
- ✱ Focus of the beam is controlled by digital voltmeters

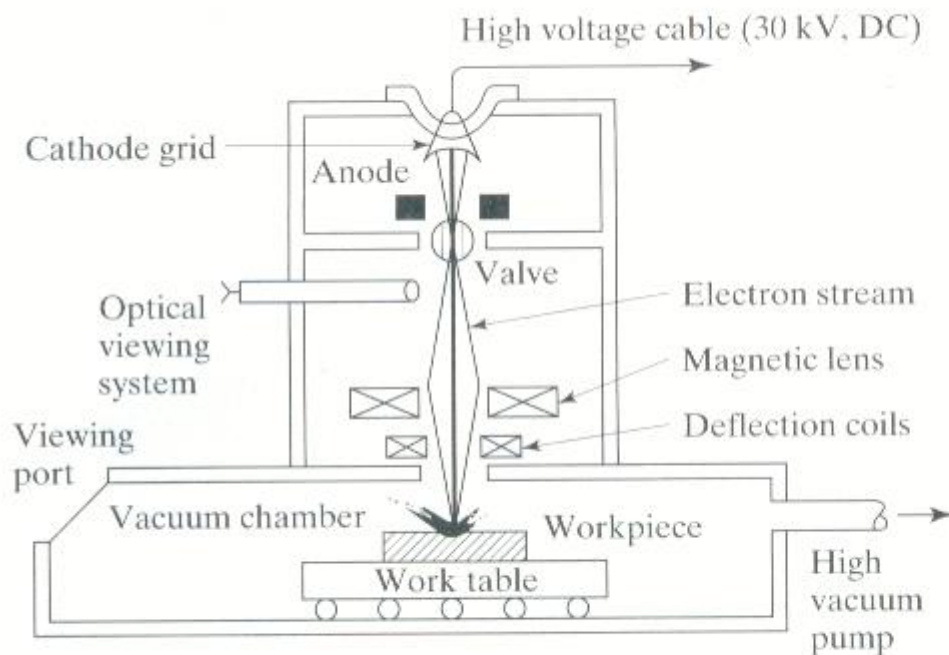


FIGURE 26.15 Schematic illustration of the electron-beam machining process. Unlike LBM, this process requires a vacuum, so workpiece size is limited to the size of the vacuum chamber.

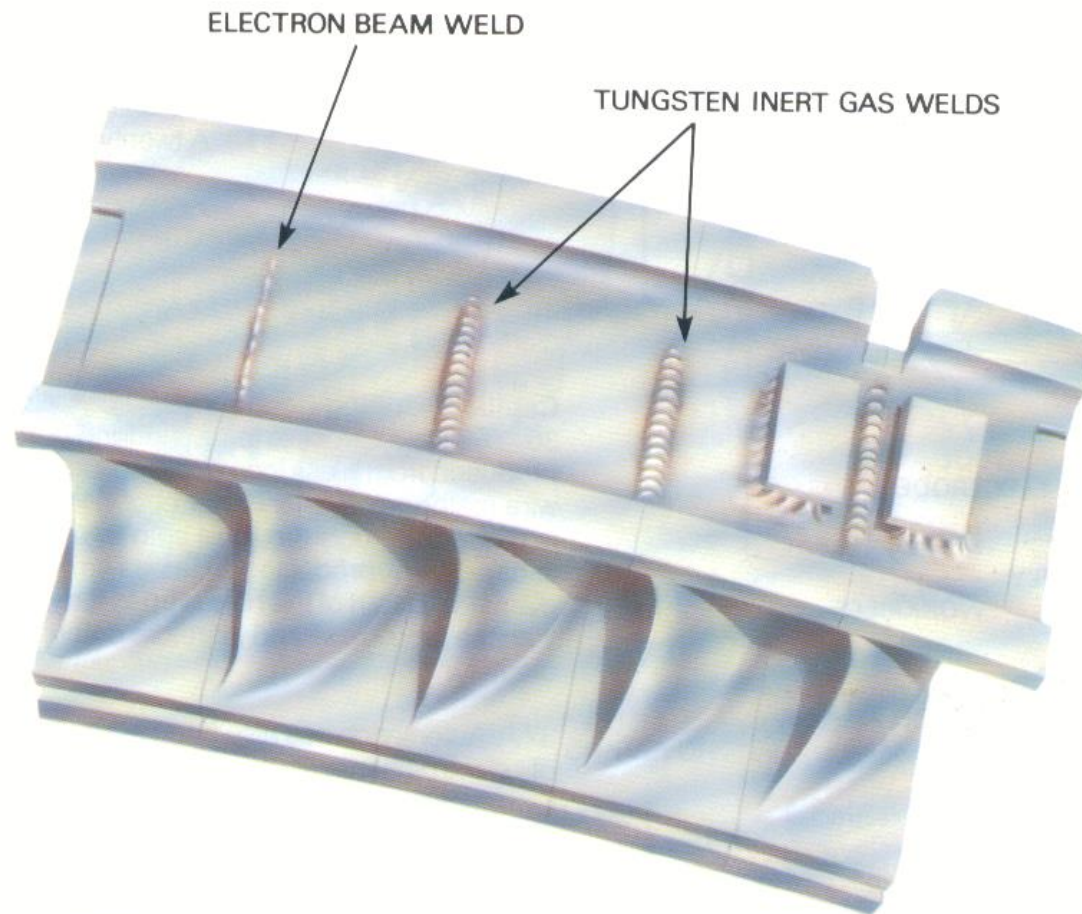


Fig. 22-10 Examples of T.I.G. and E.B. welds.

Electro-chemical machining (ECM)

- ✱ This type of machining employs both electrical and chemical effects in the removal of metal.
- ✱ Chemical forming, electro-chemical drilling and electrolytic grinding are techniques of electro-chemical machining employed in the production of gas turbine components.
- ✱ When a current flows between the electrodes immersed in a solution of salts, chemical reactions occur in which metallic ions are transported from one electrode to another. The amount of chemical reaction produced by a current is proportional to the quantity of electricity passed.
- ✱ http://www.youtube.com/watch?v=JhEXO_RPtpA&playnext=1&list=PL624C5125AEC8FFC8 Pulsed electro chemical machining

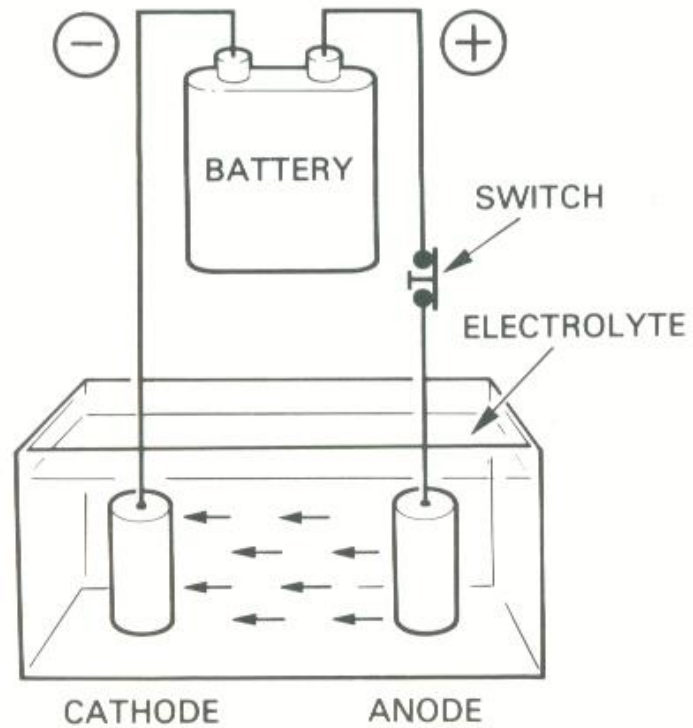


Fig. 22-11 Electro-chemical machining.

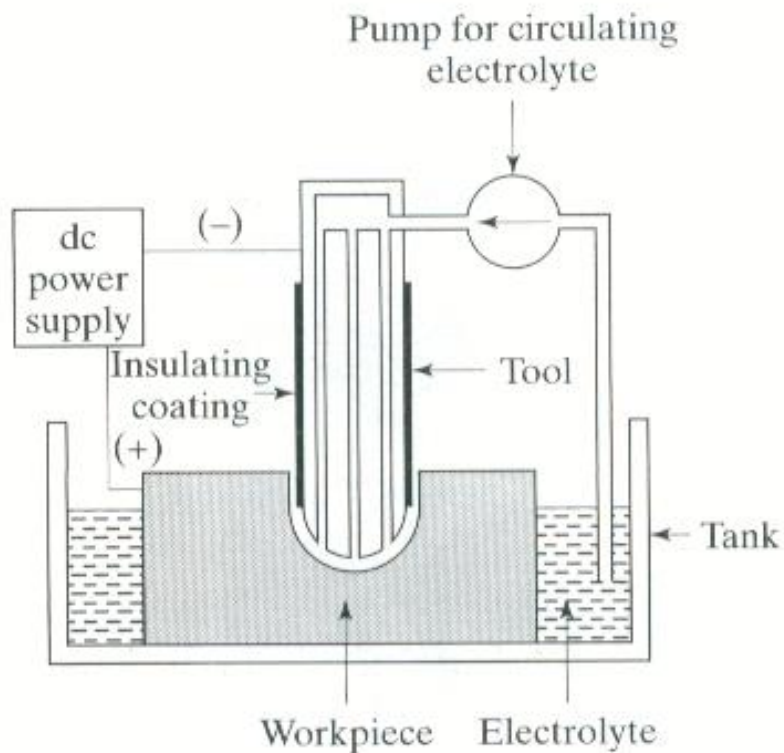


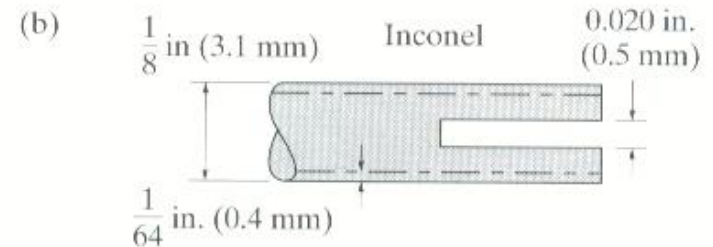
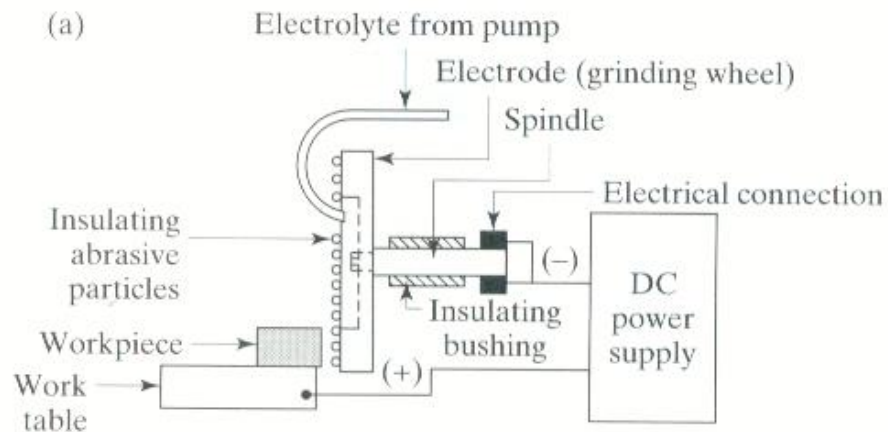
FIGURE 26.6 Schematic illustration of the electrochemical-machining process. This process is the reverse of electroplating, described in Section 33.8.

Electro-chemical machining (ECM)

- ✱ In chemical forming, fig 22-11, the tool electrode (the cathode) and the workpiece (the anode) are connected to a direct current circuit. Electrolytic solution passes, under pressure, through the tool electrode and metal is removed from the work gap by electrolytic action.
- ✱ A hydraulic ram advances the tool electrodes into the workpiece to form the desired passage.
- ✱ Electrolytic grinding employs a conductive wheel impregnated with abrasive particles. The wheel is rotated close to the surface of the workpiece, in such a way that the actual metal removal is achieved by electro-chemical means.
- ✱ The by-products, which would inhibit the process, are removed by the sharp particles embodied in the wheel.

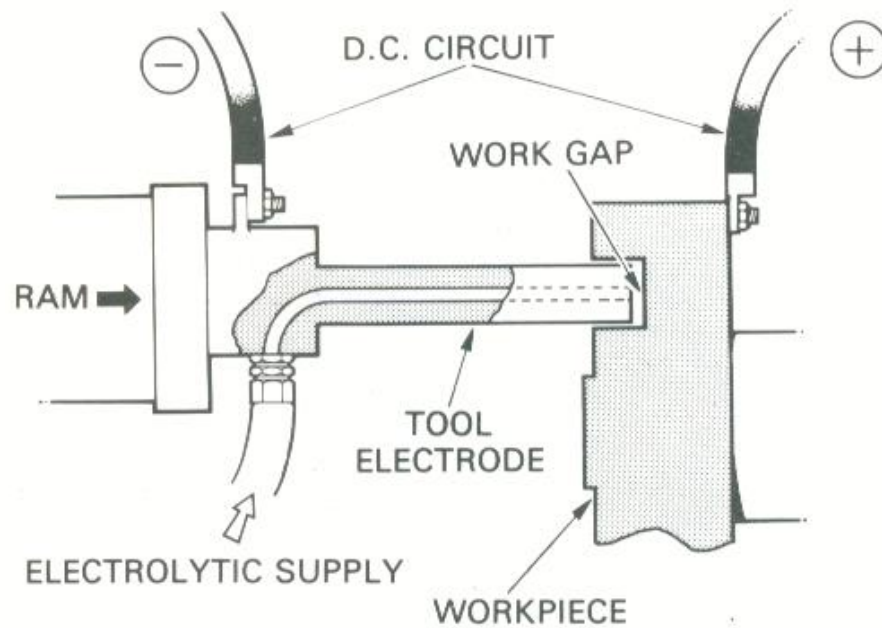
Electro-chemical machining (ECM)

FIGURE 26.9 (a) Schematic illustration of the electrochemical-grinding process. (b) Thin slot produced on a round nickel-alloy tube by this process.



Electro-chemical machining (ECM)

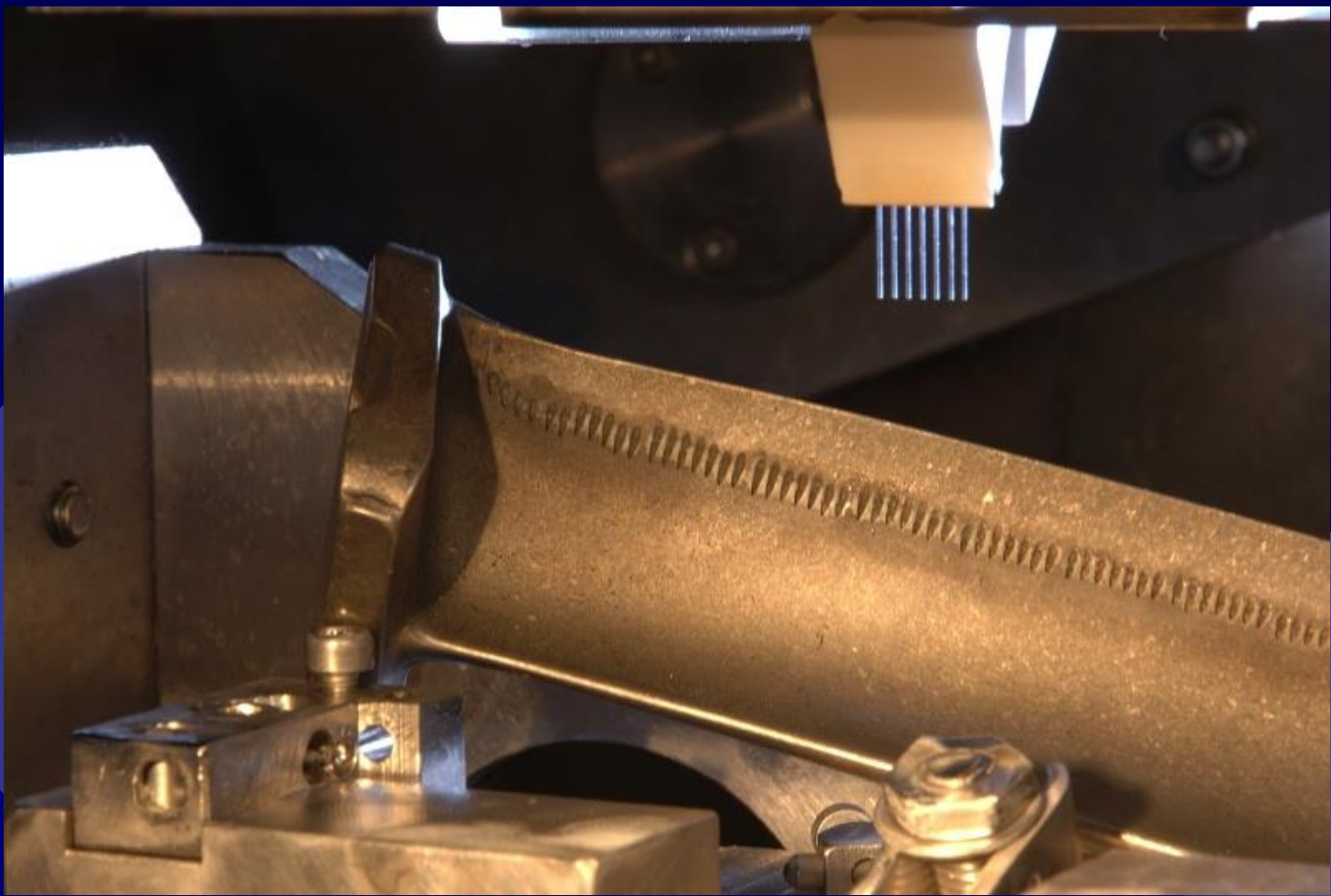
- ☀ Stem drilling and capillary drilling techniques are used principally in the drilling of small holes, usually cooling holes, such as required when producing turbine blades
- ☀ Stem drilling consists of tubes (cathode) produced from titanium and suitably insulated to ensure a reaction at the tip. A 20% solution of nitric acid is fed under pressure into the blade producing holes generally in the region of 0.026 inches diameter. The process is more speedy in operation than electro-discharge machining and is capable of drilling holes up to a depth 200 times the diameter of the tube in use.



1. Electrolytic solution passes under pressure through tool electrode
2. Tool electrode and workpiece are connected into D.C. circuit
3. Ram advances tool electrode into workpiece
4. Metal is removed in work gap by continuous electrolytic action

Electro-chemical machining (ECM)

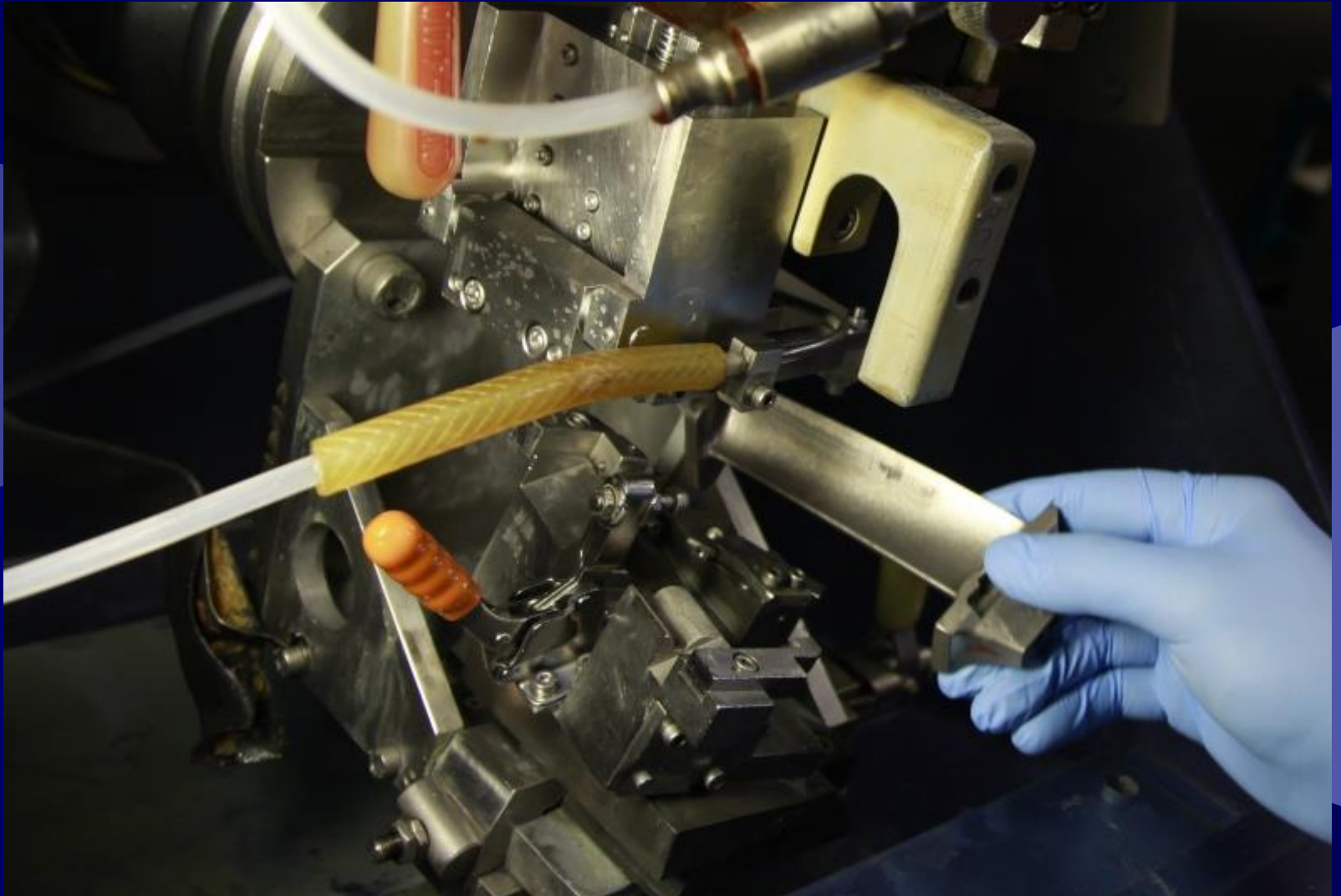
- ★ Capillary drilling is similar to stem drilling but using tubes produced from glass incorporating a core of platinum wire (cathode).
- ★ A 20% nitric acid solution is passed through the tube onto the workpiece and is capable of producing holes as small as 0.009 inches diameter.
- ★ The hole depth is up to 40 times greater than the tube in use.



Capillary drilling is an acid electrolytic drilling technique for drilling small holes in hard, corrosion resistant metals. Capillary Drilling is also referred to as Electro Streaming and is a form of ECM.

Hole diameters as small as 0.2mm/0.008" can be achieved, with depth to diameter ratio of 40:1 and multiple holes can be drilled simultaneously typically up to 100 holes.

Capillary Drilling



Electro-chemical machining (ECM)

- ✱ Automation has also been added to the process of ECM with the introduction of 360 degree ECM of small compressor blades, figure 22-12.
- ✱ Blades produced by ECM employ integrated vertical broaching machines which take pre-cut lengths of bar material, produce the blade root feature, such as a fir-tree, and then by using this as the location, fully ECM both sides to produce the thin airfoil section in one operation

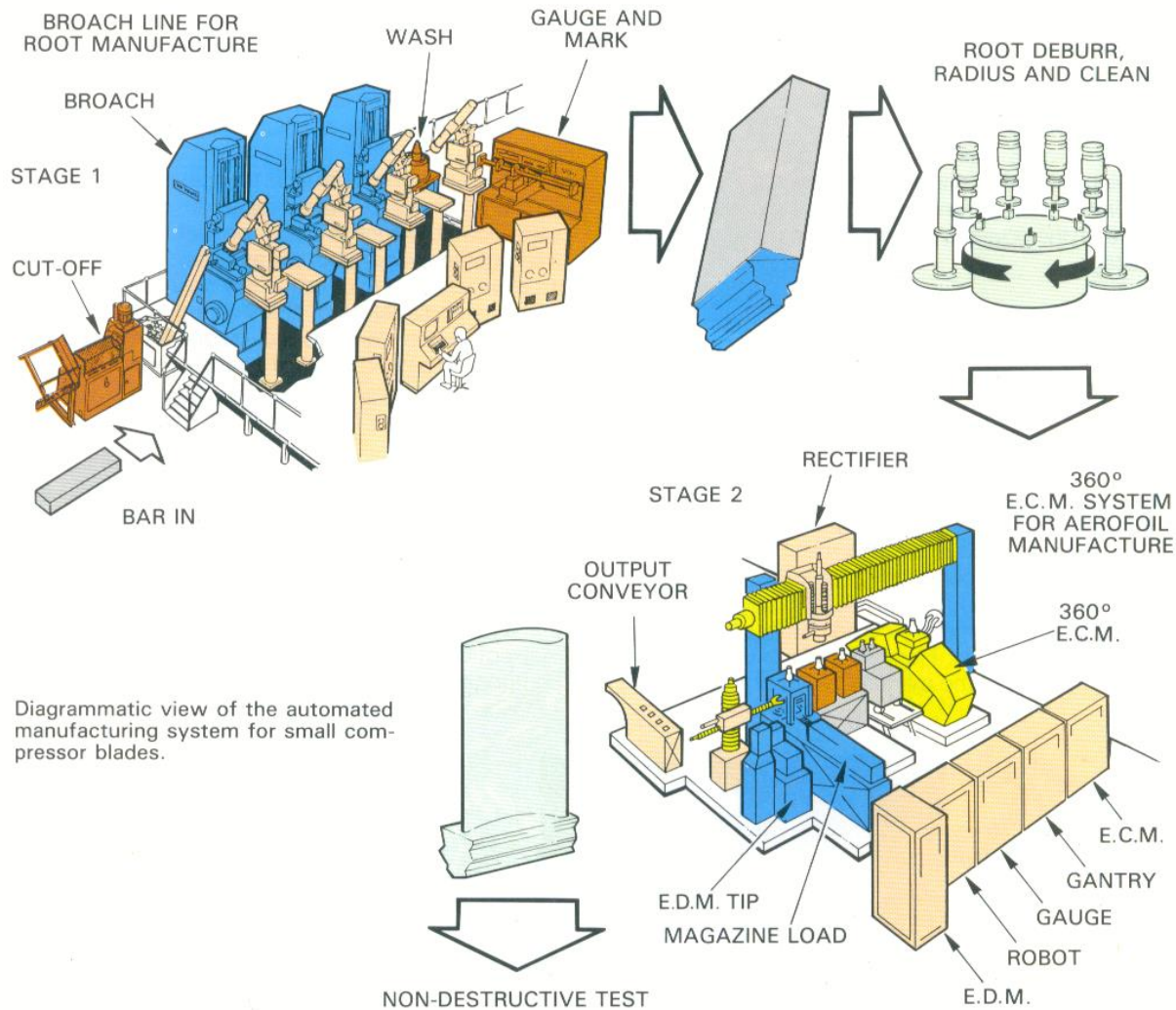


Fig. 22-12 Typical automated manufacture of compressor blades.

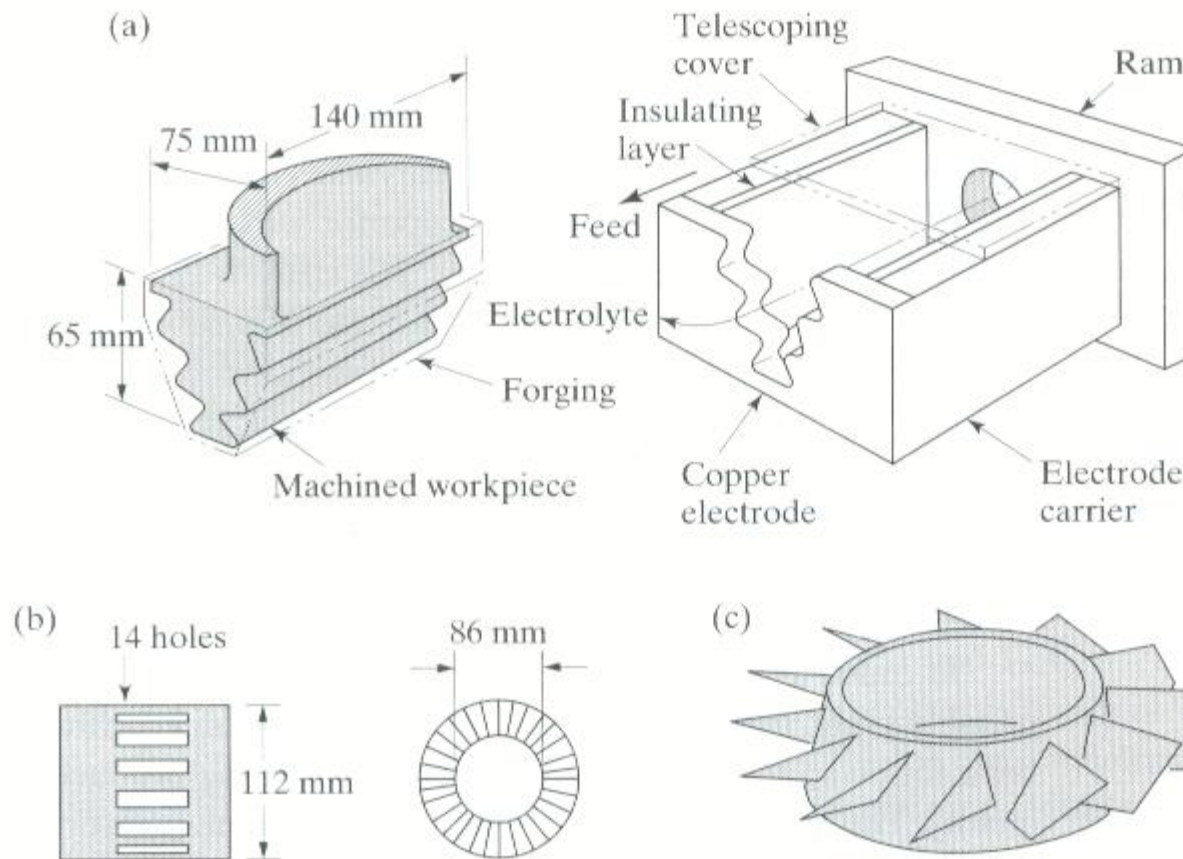


FIGURE 26.7 Typical parts made by electrochemical machining. (a) Turbine blade made of a nickel alloy, 360 HB; note the shape of the electrode on the right. *Source:* ASM International. (b) Thin slots on a 4340-steel roller-bearing cage. (c) Integral airfoils on a compressor disk.

Electro-discharge machining (EDM)

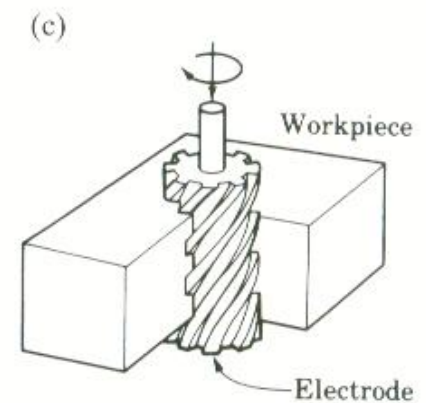
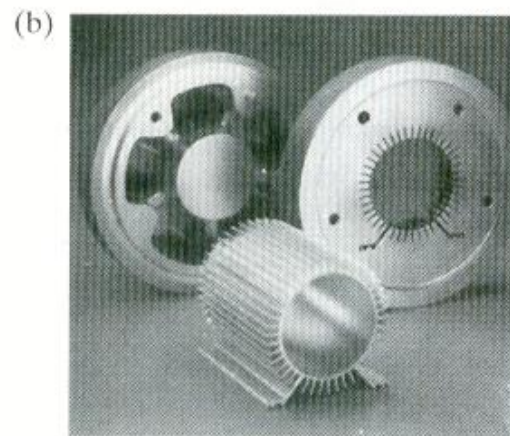
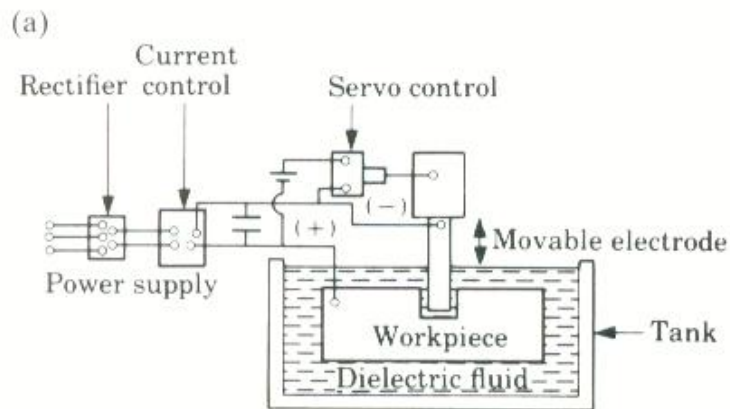
- ✱ EDM removes metal from the workpiece by converting the kinetic energy of electric sparks into heat as the sparks strike the workpiece.
- ✱ An electric spark results when an electric potential between two conducting surfaces reaches the point at which the accumulation of electrons has acquired sufficient energy to bridge the gap between two surfaces and complete the circuit.
- ✱ At this point the electrons break through the dielectric medium between the conducting surfaces and moving from negative (the tool electrode) to positive (the workpiece), strike the workpiece with great energy

<https://www.youtube.com/watch?v=2W4xZYRkWGo> EDM simulation

Electro-discharge machining (EDM)

- ✱ When the sparks strike the workpiece, the heat is so intense that the metal to be removed is instantaneously vaporized with explosive results.
- ✱ The dielectric medium, usually paraffin oil, pumped into the gap between the tool electrode and the workpiece, has the tendency to quench the explosion and to sweep away metallic vapour and molten particles.
- ✱ The shape of the electrode is a mirror image of the passage to be machined in the workpiece and to maintain a constant work gap, the electrode is fed into the workpiece as erosion is effected.

FIGURE 26.10 (a) Schematic illustration of the electrical-discharge machining process. This is one of the most widely used machining processes, particularly for die-sinking operations. (b) Examples of cavities produced by the electrical-discharge machining process, using shaped electrodes. Two round parts (rear) are the set of dies for extruding the aluminum piece shown in front (see also Fig. 15.9b). *Source:* Courtesy of AGIE USA Ltd. (c) A spiral cavity produced by EDM using a slowly rotating electrode, similar to a screw thread. *Source:* *American Machinist*.



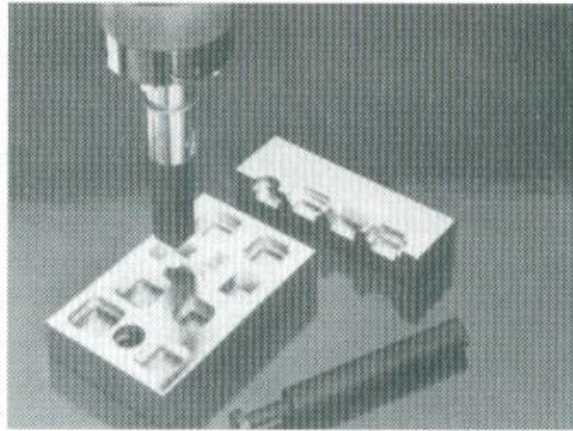


FIGURE 26.11 Stepped cavities produced with a square electrode by the EDM process. The workpiece moves in the two principal horizontal directions (x - y), and its motion is synchronized with the downward movement of the electrode to produce these cavities. Also shown is a round electrode capable of producing round or elliptical cavities. *Source:* Courtesy of AGIE USA Ltd.

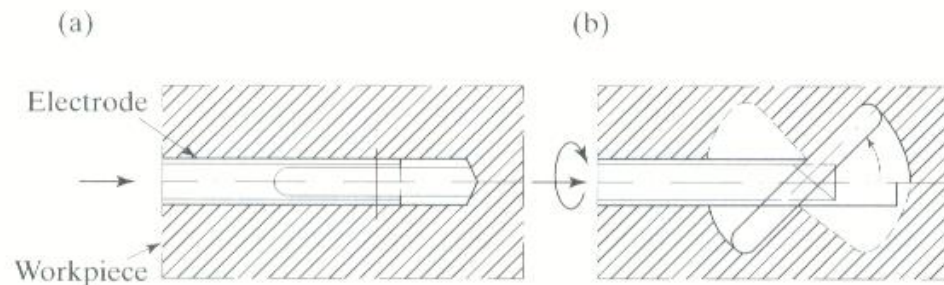


FIGURE 26.12 Schematic illustration of producing an inner cavity by EDM, using a specially designed electrode with a hinged tip, which is slowly opened and rotated to produce the large cavity. *Source:* Luziesia France.

6, 12, 20, 35 and 100kW Gas turbines

- Bladon Jets' patented, breakthrough technology enables the production of small gas turbine engines that are lighter weight, less polluting and lower cost than reciprocating engines



- ✴ Bladon Jets Turbine Components Division develops and manufactures one piece integrally-bladed rotors (IBRs) and integrally-bladed disks (BLISKs) for use in gas-turbine engines and turbo-molecular pumps and fans for bypass and vertical take-off (VTO) aero engines applications



Any material

- ★ One piece integrally-bladed turbine components can be manufactured in virtually any profile, with varying section, edge radii and taper from root to tip and from any metal/alloy
- ★ Including: aluminium alloys, nickel alloys, stainless steel and aerospace grades of titanium.

High accuracy EDM

- ★ Key technologies include the Electric Discharge Machining (EDM) spark erosion machines which are capable of creating ultra-high-precision turbine components required for the micro jets.
- ★ These components are machined from solid metal, with an accuracy of ± 5 microns

Jaguar C-X75 will become the British marque's most advanced hybrid model to date.



- ✱ It will offer performance on a par with the fastest production cars on the market, while adopting cutting-edge technology that offers remarkably economical running. Jaguar expects this hybrid supercar to deliver incredibly low CO2 emissions of less than 99g/km while being able to achieve in excess of 200mph.

Turbo molecular pumps

- ★ Turbo molecular pumps are used in scientific and research applications, such as mass spectroscopy, and in manufacturing, such as silicon chip production.
- ★ They are based on a multi-stage axial flow design, effectively a gas turbine compressor section in reverse, and are driven by electric motors running at speeds up to 90,000 rpm.



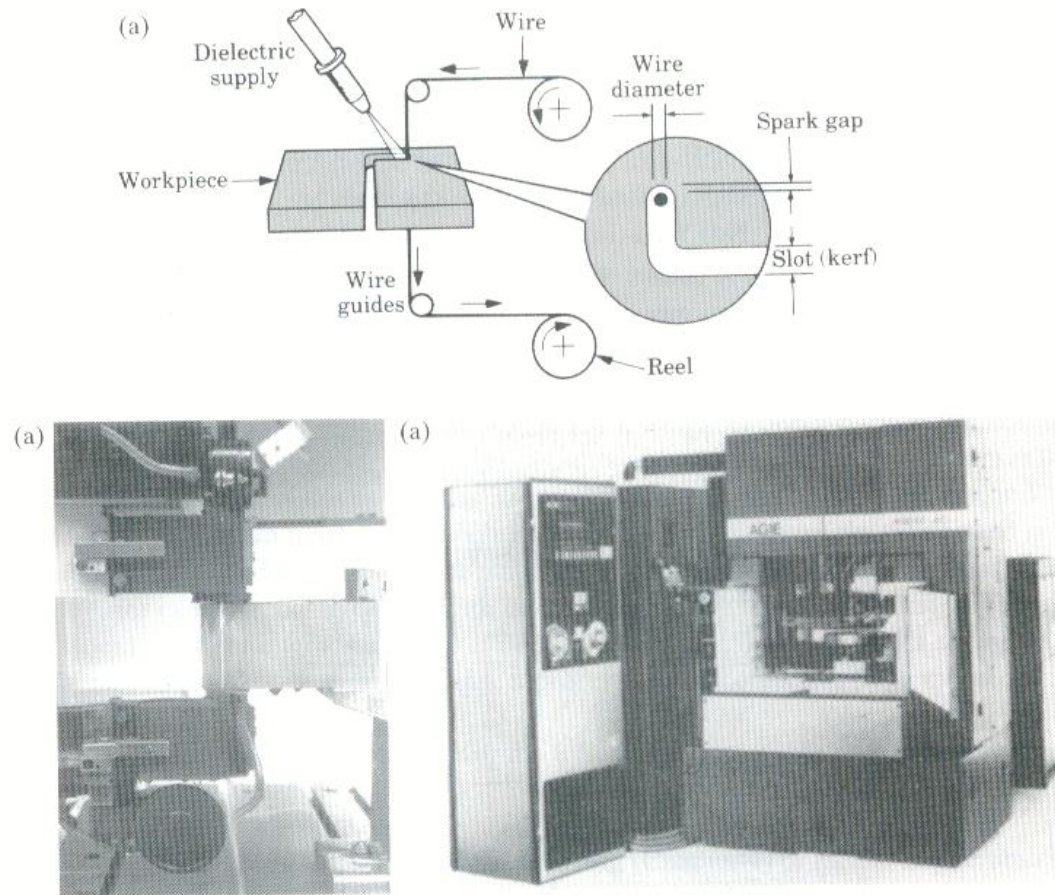


FIGURE 26.13 (a) Schematic illustration of the wire EDM process. As much as 50 hours of machining can be performed with one reel of wire, which is then discarded. (b) Cutting a thick plate with wire EDM. (c) A computer-controlled wire EDM machine. *Source:* Courtesy of AGIE USA Ltd.

Composite materials and sandwich casings

- ★ High power to weight ratio and low component costs are important considerations.
- ★ Composite materials allows the designer to produce structures in which directional strengths can be varied by directional lay-up fibres according to the applied loads.
- ★ Composite materials have and will continue to replace casings which, in previous engines, would have been produced in steels or titanium.

Composite materials and sandwich casings

- ★ By-pass duct assemblies comprising of three casings are currently being produced up to 4ft 7in diameter 2ft in length using pre-cured composite materials for the casing fabric
- ★ Flanges and mounting bosses are added during the manufacturing process, which are then drilled for location and machined for peripheral feature attachment on CNC machining centres, which at one component load , completely machine all required features.

Composite materials and sandwich casings

- ★ Conventional cast and fabricated casings and cowlings are also being replaced by casings of sandwich construction which provide strength allied with lightness and also act as a noise suppression medium.
- ★ Sandwich construction casings comprise a honeycomb structure of aluminium or stainless steel interposed between layers of dissimilar material.
- ★ The materials used depend upon the environment in which they are used.

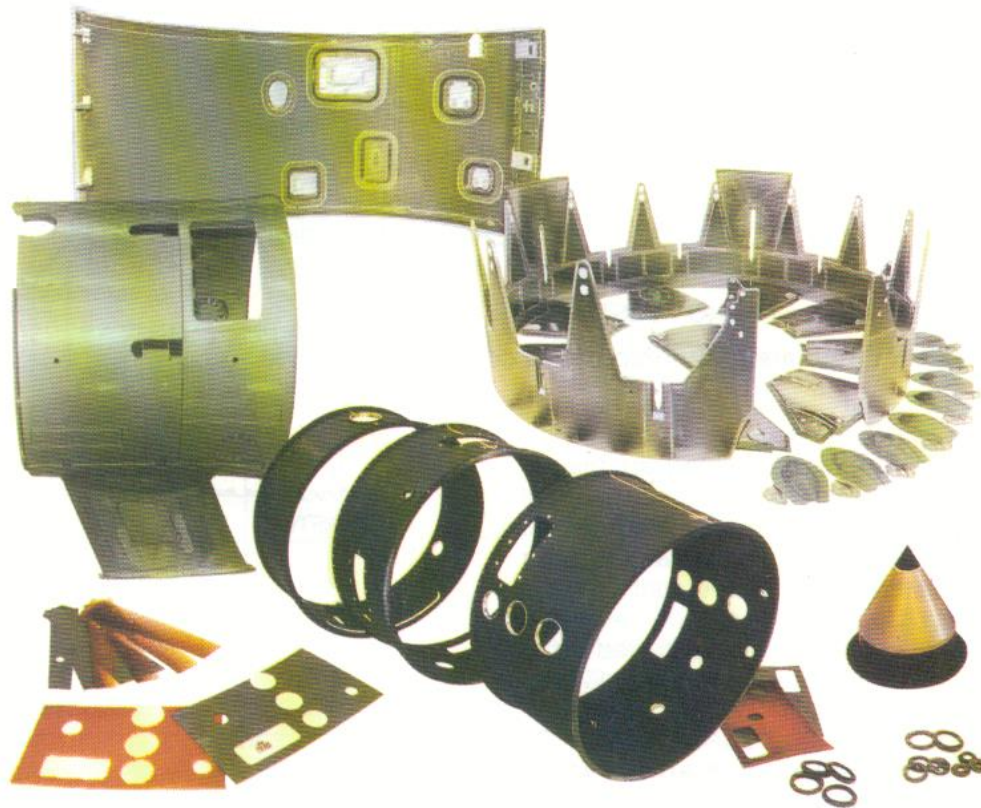
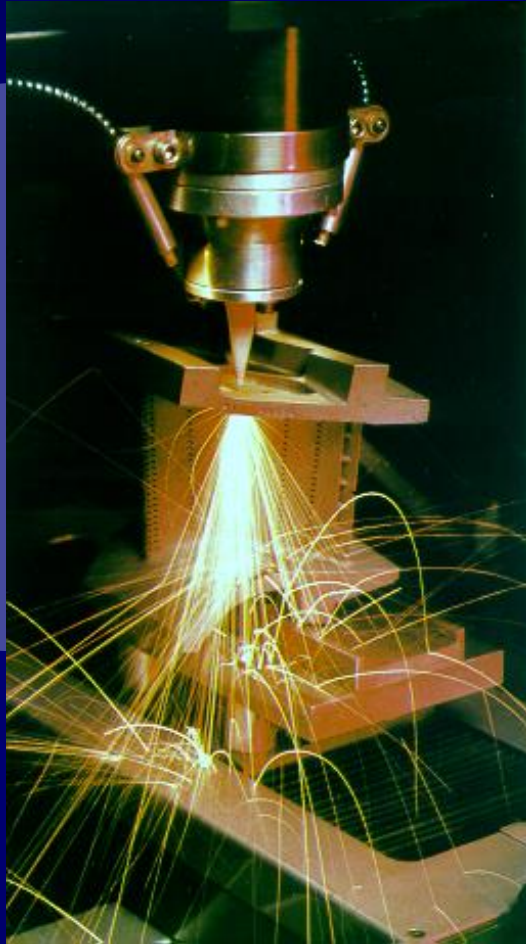


Fig. 22-14 Some composite material applications.

Nd-YAG Laser Drilling of Refractory metals



**Jet-engine turbine blade
- Nimonic alloy**



**0.5 mm holes at 20 degrees to the surface
in a jet engine combustion chamber**

Computer Numerically Controlled (CNC) Beam delivery Systems

<http://www.youtube.com/watch?v=gHjGfwf3Aeg>

<http://www.youtube.com/watch?v=UeGVbtrrHjE&NR=1&feature=fvwp>

pipes

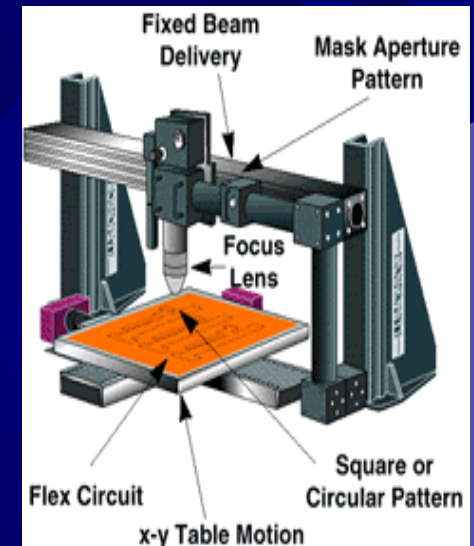
Laserdyne 550 Beam Director

Multiaxis: cutting, drilling, welding for manufacturers in aerospace, automotive and job shop industries



Laserdyne 890 Beam Director


Multiaxis: cutting, drilling, welding for manufacturers in aerospace, automotive and job shop industries





Conventional CNC machining

http://www.youtube.com/watch?v=lcGHtl9Lql4&feature=bf_next&list=PL624C5125AEC8FFC8&lf=autoplay

The background is a dark blue field filled with several interlocking gears of varying sizes and shades of blue. On the far left, there is a vertical strip of colorful, abstract, and pixelated patterns in shades of orange, yellow, and red.

End